

Highway Deicing

Comparing Salt and Calcium Magnesium Acetate

Committee on the
Comparative Costs of Rock Salt and
Calcium Magnesium Acetate (CMA)
for Highway Deicing

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Preface

Deicing chemicals, along with plowing and sanding, are important tools for highway snow and ice control. For many years, however, it has been widely acknowledged that the most popular deicing chemical, sodium chloride or common road salt, has many unintended and often costly side effects. The last major efforts to estimate the true cost of salt were conducted 10 to 20 years ago. Today, however, many of the findings from these studies are no longer accurate, because knowledge and understanding of salt's adverse effects have increased and, in some cases, significant steps have been taken to help control them. Unfortunately, the lack of more up-to-date cost information has contributed to confusion over the benefits and savings that might be achieved by using less harmful but higher-priced alternatives to salt that have been developed in recent years, such as calcium magnesium acetate (CMA).

Recognizing this need, Congress called on the U.S. Department of Transportation (DOT) to sponsor a study examining the total cost of salt and CMA, including the direct cost of application and indirect costs to the environment, infrastructure, and motor vehicles. The National Academy of Sciences was identified as an organization to conduct the study.' The National Research Council, which is the principal operating arm of the Academy, appointed a special study committee under the auspices of the Transportation Research Board (TRB) and the leadership of John J. Henry, Director of the Pennsylvania Transportation Institute at The Pennsylvania State University. Committee members are experts in chemistry, materials science, economics, environmental science, and highway engineering, operations, and maintenance.

Congress requested that the study examine the full economic costs of using salt and CMA for highway deicing. In sponsoring the study,

the Federal Highway Administration (FHWA) of DOT asked TRB to examine each deicer for both general deicing and selective uses, such as in environmentally sensitive areas and on corrosion-prone bridges. In approving the project, the TRB Executive Committee requested that the study committee also consider and comment on other promising deicing alternatives to salt and CMA when appropriate.

Much of the report focuses on defining the true cost of salt, which is the most popular deicer and the standard of comparison for most other deicing products. After reviewing the evidence, the committee estimated many of salt's costs in monetary terms, but often had to rely on a combination of sparse quantitative data, simplified assumptions, and its own expert judgment to do so. In some cases, however, a lack of sufficient information prevented even rough approximations of cost.

Although the committee debated whether to assign monetary values to environmental damages, it did not for the following reasons: (a) the environmental effects of salt vary widely by location; (b) not enough information is available to determine the extent of environmental damage, even in nonmonetary terms (e.g., number of trees harmed); and (c) the valuation of environmental damage is highly subjective. Nevertheless, the committee did present several hypothetical environmental cases in Chapter 4 that contain estimates of the monetary costs involved in correcting or mitigating environmental damage from road salt. Although these cases are not representative of all highways on which salt is applied, they illustrate the potential scale of environmental costs attributable to salt use, and they are indicative of the kinds of data and analyses that are needed to estimate the nationwide environmental costs of road salt in monetary terms.

In considering CMA, the committee summarized what is known about its field performance, compatibility with highway and automotive materials; environmental impacts, and production technologies and price. This task was complicated by the relatively small quantities of CMA used to date. Although the congressional request for the study focused on salt and CMA, at the outset of the study the committee hoped to include other deicing treatments (e.g., salt substitutes and additives) in its investigation. Whereas some references to other treatments are included in the report, the committee found too few independent analyses of them (many of which are proprietary commercial products) to draw conclusions. Salt, on the other hand, has been heavily researched, and CMA has been sub-

jected to numerous government-sponsored evaluations. As a result, the committee focused on these two products.

The committee stopped short of recommending that CMA be used in specific situations, because such conclusions can be reached only after in-depth consideration of local circumstances and all other de-icing treatments and mitigation measures available. Instead, the main purpose of the report is to provide general background information and reference material for highway agencies that may be unfamiliar with CMA, as well as those trying to get a better handle on the overall cost of their salting programs.

The final report of the committee was reviewed by an independent group of reviewers in accordance with National Research Council report review procedures.

ACKNOWLEDGMENTS

Thomas R. Menzies managed the study and prepared the final report under the guidance of the committee and the overall supervision of Robert E. Skinner, Jr., Director for Special Projects. Charles R. Goldman and John E. Reuter, consultants, wrote a commissioned paper on the effects of road salt on the environment, which formed the basis for Chapter 4. Richard D. Thomas of the National Research Council's Board on Environmental Studies and Toxicology briefed the committee on the health effects of salt in drinking water and, along with Catherine E. Woteki and Paul R. Thomas of the Food and Nutrition Board, critically reviewed Chapter 5. Joseph W. Loper analyzed computer tapes of the National Bridge Inventory file for Chapter 3. Crawford F. Jencks, Frank N. Lisle, L. David Minsk, and W. Clayton Ormsby, FHWA's technical representative, commented on drafts of the report and provided helpful technical information during committee meetings and throughout the course of the study.

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Executive Summary

Each year about \$1.5 billion is spent on highway snow- and ice-control programs in the United States. Apart from plowing, the most important element of these programs is chemical deicing, which represents about one-third of winter maintenance expenditures. Chemical deicing provides important public mobility and safety benefits by rapidly and reliably providing more driveable and less hazardous road conditions during the winter months. The benefits are difficult to quantify but are widely acknowledged to be valuable to society.

Sodium chloride, or common road salt, is by far the most popular chemical deicer, because it is reliable, inexpensive, and easy to handle, store, and apply. Since 1970, highway agencies have applied an average of approximately 10 million tons of road salt each winter. Over the years, however, the widespread use of salt has been linked with many indirect costs, including damage to motor vehicles, infrastructure, and the environment. Recognizing these drawbacks, in 1980 the Federal Highway Administration identified calcium magnesium acetate (CMA) as a possible replacement for salt. Since its discovery, CMA has been the subject of many laboratory and field studies to determine its deicing performance, environmental acceptability, and compatibility with automotive and highway materials. Results have been promising, but the most significant impediment to its use has been its price, which is more than 20 times that of salt.

The commercial availability of CMA and continued concerns about the indirect costs of salting have underscored the need for more information on the total cost of deicing. Recognizing this need, in 1988 Congress requested a study comparing the true costs of salt and CMA, including direct application costs and indirect costs to the environment, human health, motor vehicles, and infrastructure. A special committee of the Transportation Research Board carried out the study. The committee focused most of its efforts on determining

the true cost of salting, which was last estimated 15 years ago for the Environmental Protection Agency. In addition, the committee reviewed what is known about CMA as a deicer and identified major cost and use issues that need to be addressed when CMA is considered as a replacement for salt.

ROAD SALT DAMAGES AND COSTS

The main side effects, or indirect costs, of salting are (a) motor vehicle and infrastructure damage, (b) degradation of the environment along the roadside, and (c) sodium infiltration of drinking water.

Motor Vehicle and Infrastructure Costs

Salt damages motor vehicles and infrastructure primarily because of its corrosive effects on metals. The chloride ions in salt disrupt natural protective films on metal surfaces and increase the conductivity of water, which induces and accelerates corrosion. By far the most costly damage is to motor vehicles, followed by bridges and parking structures. Less obvious side effects, which collectively may be significant, include damage to concrete pavements, underground utilities, and roadside objects.

Motor Vehicles

During the 1960s and 1970s, the increased use of sodium chloride for highway deicing, combined with acid precipitation from atmospheric pollutants, sea spray in coastal areas, and the use of calcium chloride for low-temperature deicing and dust control, resulted in widespread corrosion in vehicles throughout the Northeast and Midwest. Besides affecting the appearance of vehicles, corrosion affected the structural condition and function of critical vehicle parts, such as brake linings, floor panels, and frame and bumper systems.

Automobile manufacturers have made gradual advances in reducing corrosion during the past 20 years by improving vehicle designs, materials, and manufacturing processes. It is anticipated that these advances will continue to reduce the incidence and severity of corrosion. During the past decade, these advances have led to the virtual elimination of salt-induced structural and functional corrosion, and

cosmetic corrosion has been greatly reduced. Today the most clearly identifiable cost of road salt is the more expensive corrosion-resistant materials and coatings used in new cars and trucks. Altogether, corrosion protection features that are directly related to road salt have increased the cost of manufacturing new vehicles by approximately \$1.9 billion to \$3.9 billion per year.

Besides bearing the expense of this protection, motorists in salt-using regions also spend additional time and money trying to prevent persistent cosmetic corrosion, for example, by more frequent car washing and careful touching up of paint damage caused by stone chips and minor accidents. Only limited data are available to estimate the cost of this additional maintenance and any losses in vehicle appearance and value due to cosmetic corrosion that persists. The committee believes that a plausible range for this cost is \$1 billion to \$2 billion per year, but that the cost will continue to decline during the next 10 years because of continued progress in corrosion prevention.

Bridges

Among the components of highway infrastructure, road salt is most clearly damaging to bridge decks. The chloride ions in salt penetrate concrete and cause reinforcing steel bars (rebars) to rust, resulting in cracking and fragmenting of the surrounding concrete. Though this damage seldom compromises the structural integrity of a properly maintained deck, it can cause extensive potholing of the deck surface, which can seriously degrade deck ride quality.

During the past 30 years in the Northeast and Midwest, road salt has caused more premature bridge deck deterioration than any other factor. After decades of salting, thousands of older decks are critically contaminated with chloride and will continue to deteriorate whether salt or noncorrosive deicers are used. Repair and restoration of these contaminated decks as they become deficient is likely to be a major, and largely unavoidable, expense for many years. Accordingly, an urgent concern is to protect newer decks that are not already contaminated. New construction techniques and materials have been developed in recent years that promise to reduce both the incidence and severity of deck damage. Most decks built in the past 10 to 20 years in snowbelt states are equipped with some type of protection. During the next 10 years, the total cost of installing these protections during the construction of new decks and repairing the portion of

currently sound decks that become damaged by continued salting will be about \$125 million to \$325 million per year.

Bridge components other than concrete decks that are vulnerable to salt-induced damage include reinforced concrete supports (e.g., beams), steel structural supports, bearings, and joint devices. Damage to these components, which is caused by salt leaking from the deck and salt splash and spray from adjacent roadways, is generally less extensive than deck damage but is often more difficult and expensive to repair and protect against. Although the information available to quantify these costs is limited, the committee believes that collectively they are as large as deck costs and, as a rough approximation, fall within the same range, \$125 million to \$325 million per year.

Parking Garages

There are about 5,000 large, multilevel parking garages in the Northeast and Midwest. During the past 20 years, hundreds have become contaminated and seriously damaged by salt dropped from parked cars. The process is similar to that of bridge decks; salt intrusion causes the reinforcing steel to rust, in turn causing cracking and fragmenting of surrounding concrete. Like bridge decks, many older parking garages are critically contaminated with salt and will need to be repaired or demolished regardless of future salt use. Accordingly, an urgent concern is protecting newer garages not already contaminated with chloride. Most new parking garages are equipped with some type of protection against corrosion, which should reduce damage in the future. During the next 10 years, the total cost of installing these protections and restoring garages that become damaged by continued salting will be roughly \$75 million to \$175 million per year.

Other Infrastructure

Other infrastructure components affected by road salt include non-bridge highway components, such as reinforced concrete pavements and roadside hardware (e.g., signposts and light stands); objects buried under or alongside highways, such as utility lines, pipelines, and steel storage tanks; and some nonhighway objects near salt-treated roads, such as bronze monuments. For many of these items,

repair and maintenance requirements due to corrosion (from numerous sources) and other sources of damage are serious problems with large annual costs. Available data, however, are insufficient to isolate the incremental effect of road salt on this much broader set of infrastructure costs.

Summary

The committee's estimates of annual salt costs associated with motor vehicles and infrastructure are summarized in Table ES-1. The reliability of these estimates varies, and some cost items are not quantified because of inadequate information. Summation of the more reliable cost estimates, for which supporting data are relatively dependable, suggests a minimum vehicle- and infrastructure-related

TABLE ES-1 SUMMARY OF ANNUAL COSTS FOR MOTOR VEHICLES AND INFRASTRUCTURE FROM CONTINUED SALTING

Cost Item	Annual Cost (\$ millions)
Category I (Data Reliable and Complete)	
Motor vehicle corrosion protection	1,900–3,900
Bridge decks	125–325
Parking structures	75–175
Total	2,100–4,400
Category II (Estimates Based on Committee Judgment)	
Motor vehicle corrosion damage	1,000–2,000 ^a
Bridge nondeck components	125–325
Other highway components	100 ^b
Total^c	1,200–2,400
Category III (No Reliable Data Available)	
Roadside objects	N.A.
Underground objects	N.A.
User costs ^d	N.A.

NOTE: N.A. = not available.

^a From an illustration in Chapter 3 of the potential magnitude of these costs if car buyers in salt-using states are willing to spend an additional \$125 to \$250 per new car (the cost of existing salt protection) to eliminate persistent cosmetic corrosion.

^b Cost totals less than \$100 million, assuming it is an order of magnitude smaller than total bridge costs.

^c Rounded to nearest \$100 million.

^d Examples include user costs associated with salt damage and repair to bridge decks and parking garages.

cost ranging from approximately \$2 billion to \$4.5 billion per year. Inclusion of other cost items that are based heavily on committee judgment provides a more complete, although less precise, cost estimate ranging from approximately \$3.5 billion to \$7 billion per year.

Among the cost items omitted from these estimates because of insufficient information are damage to roadside objects, corrosion of underground materials and structures, and costs incurred by motorists who are inconvenienced by bridge and parking garage damage and repair work. These costs are difficult to quantify but are potentially significant in specific situations.

Environment

During the past three decades, hundreds of reports have been written documenting the effects of road salt on the environment. The literature clearly indicates that the effects can be significant but depend on a wide range of factors unique to each site. Most frequently reported in the literature are damage to roadside vegetation, soil, and surface water.

Vegetation

Roadside trees and other vegetation can be injured by salt through changes in soil chemistry and splash and spray on foliage, shoots, and branches. The primary concern is excessive exposure to chloride. The symptoms of chloride injury are similar to those of drought: inhibited growth, browning and falling leaves and needles, and sometimes dying limbs and premature plant death. The extent of damage varies greatly by location and depends on factors such as degree of salt use, topography, precipitation, drainage, weather conditions, and vegetation cover and species. Damage is most likely to occur along downsloping roadsides (which result in greater salt runoff and allow salt spray to reach treetops) along primary highways, because high speeds and traffic volumes are associated with greater salt use and salt spray.

Highway agencies in states in which public concern about vegetation damage is greatest report that 5 to 10 percent of the roadside trees (those within 100 ft of the pavement edge) along some sections of salt-treated primary highways exhibit signs of salt-related decline. In general, they report less significant damage on secondary highways

and that common roadside shrubs and grasses tend to tolerate salt better than do trees.

Soil

Salt's effect on soil is usually confined to 15 ft of the pavement edge. The primary concern is long-term sodium accumulation, which can adversely affect soil structure characteristics. Specifically, sodium accumulation can increase soil density and reduce permeability, moisture retention, and fertility, which affect plant growth and erosion control. However, whether salt has a cumulative effect depends on local conditions, such as soil type, precipitation, and topography.

Surface Water

Salt's effects on surface water are confined mainly to small streams running adjacent to heavily salted highways. Although small receiving lakes and ponds can be affected, few such incidents have been reported in the literature. In general, salt loadings in larger rivers and lakes are diluted because of high water volumes. In extreme cases, high and persistent chloride concentrations in roadside streams can harm fish and other stream life. The complexity of stream environments and the absence of detailed data make it difficult to characterize and quantify possible adverse effects on a national basis.

Summary

In summary, each report of salt damage to the environment must be reviewed in the light of prevailing conditions at the particular site; hence, reliable nationwide estimates of environmental damage and resultant costs are not possible. Though such evaluations have been attempted in the past, they were not intended, nor are they accurate enough, to compare the overall cost of salt with that of alternatives. Meaningful estimates of environmental damage can only be accomplished on a case-by-case basis by evaluating local circumstances in depth. Even when environmental damage can be quantified for a specific site, a monetary value can be difficult to assign and highly subjective. Estimates of remediation costs—such as the expense of removing and replacing an injured tree—provide some cost perspective, but they may be inaccurate or incomplete because they do

not reflect the value of the injured tree to society or other indirect costs, such as diminished roadside aesthetics and secondary effects on the roadside ecosystem.

Drinking Water

Road salt can enter drinking water supplies by migrating through soil into groundwater or by runoff and drainage directly into surface water. In general, only wells or reservoirs close to salt-treated highways or salt storage facilities are susceptible to salt infiltration. Susceptibility depends on many factors, such as salting intensity, soil type, climate, topography, and water volume and dilution. Sources of salt in drinking water other than road salt include natural brines and salt deposits, industrial and agricultural chemicals, and water treatment and softening processes.

During the past 30 years, communities in several states, primarily in the Northeast, have reported higher sodium and chloride concentrations in private wells and public water supplies that have been linked to road salt. Many of these problems resulted from improper salt storage. Most of the more egregious salt storage problems are being corrected. Some communities report salt concentrations in water supplies due to highway runoff, although such concentrations are seldom as high as those associated with improper salt storage.

The discovery of higher salt concentrations in drinking water due to road salt has raised concerns about possible adverse effects on public health. Salt is a source of dietary sodium. Excess dietary sodium has been negatively associated with health primarily because of concerns related to hypertension, or high blood pressure. Typically, drinking water and all other beverages combined account for less than 5 percent of daily sodium intake. Because of the normally minor contribution of drinking water to sodium intake, no federal standards have been established for salt (i.e., sodium or chloride) concentrations in water supplies.

Efforts to mitigate the amount of salt in drinking water vary from state to state and by community. Common measures include modifying highway drainage, relocating private wells, upgrading salt storage facilities, and reducing salting activity in the vicinity of public water supplies. Nationally, about \$10 million is spent on mitigation each year by state and local governments, mostly in the Northeast and Midwest.

CMA

Since 1980, numerous laboratory and field studies have been conducted to evaluate CMA's field performance, likely impacts on the environment and human health, compatibility with automotive and highway materials, and prospective production technologies and market price. Findings from published reports of CMA field evaluations and interviews with current CMA users indicate the following:

- **Field experience:** To date, CMA has had limited use, which complicates efforts to determine its likely performance under a wide range of conditions. In the selective and experimental situations in which it has been used, it has often performed acceptably, although generally not in the same manner and not quite as effectively or consistently as salt. Compared with salt, it is slower acting and less effective at lower temperatures [below -5°C (23°F)] and in freezing rain, drier snowstorms, and light traffic. The timing of application is more critical than for salt. If application is delayed, its deicing performance is notably reduced. CMA is usually applied in greater quantities (by weight) than is salt—usually by 20 percent or more—though specific quantities vary by storm and user. Because of its lower density and greater volume requirements, CMA may require substantially more truck capacity and enclosed storage space (60 percent or more) than salt, especially for more general use.

- **Health and environmental effects:** Research findings to date indicate that CMA is likely to have no adverse effects on human health and few negative environmental effects. Because it is biodegradable and exhibits poor mobility in soils, it is less likely than salt to reach groundwater. In preliminary environmental evaluations, the potential for CMA to extract heavy metals from roadside soils was identified; however, results from follow-up studies have not indicated this effect. CMA has exhibited negligible adverse effects on common roadside vegetation and is apparently safe for use near most aquatic environments, although the effect of heavy CMA treatments near some small, poorly flushed, or poorly diluted ponds and streams may require monitoring and further study. These findings may not apply to CMA derived from some alternative feedstocks, such as municipal solid waste, which may introduce contaminants that alter its known environmental effects or create new ones.

- **Compatibility with motor vehicles:** CMA is more compatible with most automotive materials and components than is salt. Vir-

tually all automotive metals, plastics, coatings, parts, and components tested in laboratory experiments have exhibited fewer negative reactions when exposed to CMA than when exposed to salt. The potential for CMA spray to adhere to vehicle windshields and body parts, which has been reported by some field users, would probably require further study before more widespread use.

- **Compatibility with highway and bridge materials:** Laboratory tests indicate that CMA is less detrimental than salt to common highway materials, including those used for paving, road marking, and highway construction. CMA is much less corrosive than salt to exposed steel and other metals commonly used on bridges for applications such as joints, gutters, railings, and beams. Recent findings also indicate that CMA is less corrosive than salt to rebars in new concrete and does not accelerate corrosion of rebars in older, chloride-contaminated concrete. However, there is insufficient evidence to determine whether CMA reduces the rate of corrosion in concrete that is already contaminated with chloride, which is the condition of many older bridges in the Northeast and Midwest.

- **Production technologies and price:** CMA is manufactured by reacting dolomitic lime with acetic acid, which is CMA's chief cost component. The only CMA on the market is manufactured by using acetic acid derived from natural gas. It is priced between \$600 and \$700 per ton delivered. Alternative, lower-cost production technologies are being investigated. Given the uncertain prospects of these technologies and the long-term schedules required to introduce new manufacturing processes, prices on the order of \$600 to \$700 per ton are the only reasonable projections that can be made now.

CMA COST AND USE ISSUES

Cost issues related to both the general and selective use of CMA were reviewed by the committee.

General CMA Use

The committee believes that the use of CMA as a more general replacement for salt is unlikely and unwarranted. Widespread use of CMA would probably reduce corrosion of some motor vehicles and infrastructure components that are poorly protected and not already contaminated by salt. However, its widespread use would

have little effect on the corrosion of many older, salt-contaminated infrastructure components or on many other costs related to corrosion prevention. Even in the absence of road salt, the continued corrosivity of the highway environment due to atmospheric pollution (acid precipitation), the continued use of other chloride chemicals (such as calcium chloride for low-temperature deicing and dust control), and salt spray in coastal regions would make much of this corrosion protection necessary. In addition, because salt's environmental impacts are site specific, it is not clear that widespread use of CMA would result in significant environmental savings that could not be achieved by less expensive, targeted mitigation measures (which might include selective CMA treatments).

If a moderate- or large-scale conversion to CMA were made, highway agencies would learn how to use CMA more effectively and efficiently—for example, by modifying equipment and adopting spreading, handling, and storage practices better suited to CMA. Nevertheless, such a conversion would have far-reaching effects on winter maintenance budgets and operations, both during the initial conversion and in the long term. Given CMA's higher price and greater volume requirements—which would be likely to require substantially more storage space, spreading equipment, and manpower—expenditures on deicing material would increase by 20- to 30-fold, and winter maintenance budgets would increase by a factor of five. In practice, because CMA is slower acting than salt and does not always perform as well in light traffic, freezing rain, and dry and cold storm conditions, its widespread use could present significant operational difficulties to highway agencies. In particular, the need to apply CMA early during a storm cycle could pose problems for highway agencies without enough manpower and equipment to provide early coverage on all highways.

Selective CMA Use

Currently, CMA is used selectively and in limited quantities, primarily in environmentally sensitive areas and on new (uncontaminated) corrosion-prone structures and highway sections. On the basis of existing information about CMA's deicing performance and cost, the committee believes that such selective applications are likely to be the principal uses for CMA in the future. CMA's cost-effectiveness in such situations can only be determined on a case-by-case basis, after considering the relative costs of CMA, salt, alternative deicing

materials, and other measures to mitigate salt's adverse effects. This is especially true for environmentally sensitive areas, because each roadside has a unique environment and valuations of environmental damage vary by location. For all potential use situations, however, consideration must be given to other means of reducing salt costs, such as protection from corrosion, modification of highway drainage, improvement of deicer application techniques, and more vigilant salt management.

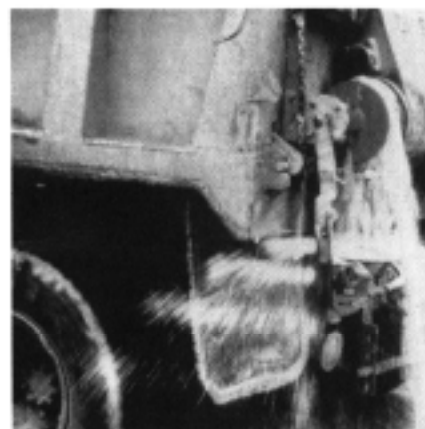
OUTLOOK FOR REDUCING DEICING COSTS

More than 20 years after the adverse side effects of road salt first came to light, the total cost of salting continues to be high. During this period, however, major achievements in corrosion protection have helped control many costs and are expected to continue to do so. Carefully designed and located salt storage facilities and better-managed salting programs should help reduce environmental damage and water contamination.

In all likelihood, sodium chloride, or common salt, will continue to be the predominant highway deicer for many years. Highway agencies and private industry continue to refine and seek new ways to prevent and treat salt's adverse effects, for example, by improving corrosion protection and developing new corrosion repair methods. Likewise, research continues aimed at reducing salt use by developing anti-icing technology (e.g., chemicals for pretreating roadways to prevent ice formation), improving salt application techniques, and exploring alternatives to salt besides CMA. CMA is therefore one of many options available to highway agencies to mitigate salt's adverse effects, and its use and acceptance is likely to depend in large part on the progress made in other mitigation areas.

2

Road Salt Use in the United States



Under many snow and ice conditions, the use of deicing chemicals is necessary to maintain clear pavements. In terms of both time and budget, common salt, or sodium chloride, is widely regarded as the most effective means of deicing highways. Salt is by far the most commonly used

deicing chemical in the United States; it is spread at a rate of approximately 10 million tons per year.

This chapter provides general background information on the use of road salt, including trends in usage, application and storage practices, use by region and jurisdictional level, and annual spending on salting operations. The chapter concludes with a brief discussion of some of the benefits of deicing and efforts being made by highway agencies to manage their salting programs.

TRENDS IN ROAD SALT USE

The use of road salt has paralleled changes in the size and importance of the nation's highway system. Before the 1940s, highway departments relied mostly on plowing and abrasives (e.g., sand and cinders) to keep roadways open after winter storms. Salt was used primarily as an additive to prevent freezing of sandpiles. During the winter of 1941–1942, New Hampshire became the first state to adopt a general policy of using salt, although a total of only 5,000 tons of salt was spread on the nation's highways that winter (TRB 1974, 2).

After World War II, as the expanding highway system became essential to the public and the national economy, road salt use began to soar. The bare-pavement concept, under which motorists could expect snow- and ice-free pavements shortly after storms, soon became a policy in most cities and their suburbs. As a result, salt use doubled every 5 years during the 1950s and 1960s, growing from 1 million tons in 1955 to nearly 10 million tons less than 15 years later (Figure 2-1).

Road salt use has leveled off during the past 20 years. Whereas salt use increased rapidly during the 1950s and 1960s because it was replacing abrasives, by the 1970s this conversion was nearly complete. Also, at about this time, many of salt's adverse effects were becoming well known, causing many highway agencies to reevaluate their salting practices. Through practical experience and with guidance from government and industry, many highway agencies started managing their salting programs, for example, by calibrating spreading equipment and establishing formal salt use policies. Partly because of these changes, annual salt use has fluctuated from 8 million to 12 million tons during the past 20 years, with year-to-year fluctuations depending mainly on winter conditions.

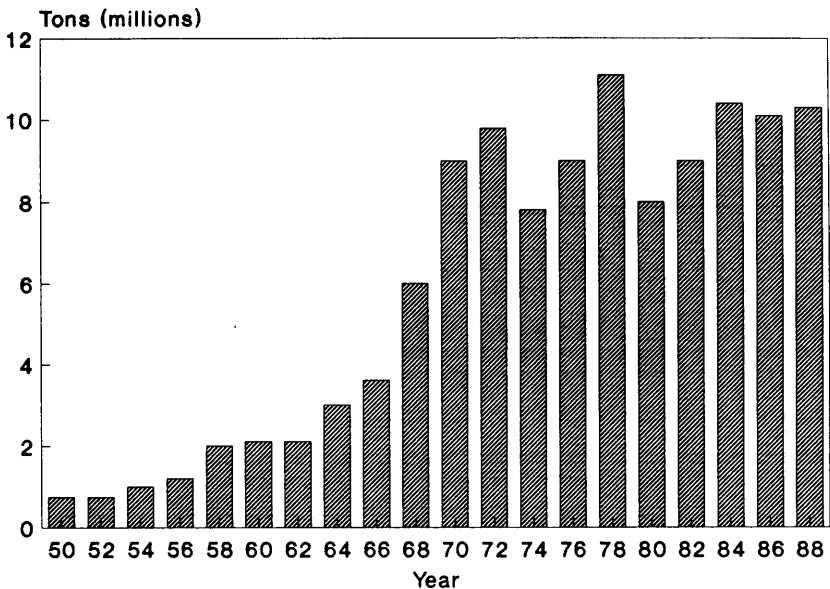


FIGURE 2-1 Trends in highway salt use, 1950–1988 (source: Salt Institute).

SALT APPLICATION AND STORAGE

Early in the century, when salt was used selectively on busy city streets, it was often shoveled from the back of trucks. As its use grew, innovations were made in salting equipment and practices. During the 1950s and 1960s, spinning disks and rollers extending the width of the truck were introduced to allow spreading over a wide path. Later, many highway agencies learned to spread salt more efficiently by windrowing it in a narrow line to produce concentrated brines that flowed under the ice to break the pavement-ice bond. Other methods of applying salt include the direct dispensing of salt solution from trucks equipped with a tank and nozzle and the use of “prewetted” salt dampened with water or liquid calcium chloride. Because prewetted salt adheres well to the pavement (reducing wind and traffic scatter) and acts faster than dry salt (by dissolving faster), less deicing chemical is required.

Salt Application Rates

Salt melts ice by depressing the freezing point of water.¹ The addition of salt to water lowers the freezing point of the solution until the salt concentration reaches about 25 percent. This threshold concentration marks the eutectic point, at which the freezing temperature of the solution can no longer be lowered, and the addition of more salt has no additional ice-melting effect. The eutectic temperature for salt solution is -21°C (-6°F). Under field conditions, however, ice melting is much too slow near the eutectic temperature to be of practical significance. At pavement temperatures below -12°C (10°F), sodium chloride is seldom used, and highway agencies rely more on sanding or salt mixed with calcium chloride, which remains effective in cold conditions.

As a practical matter, at pavement temperatures above -12°C (10°F), the amount of salt needed for highway deicing is usually less than the theoretical amount necessary to melt all the ice. If applied properly, small amounts of salt usually produce partial melting and flowing brines that break the bond between pavement and ice and thereby allow accumulations to be removed by the action of traffic or plowing (TRB 1974). Usually, highway maintenance engineers are given flexibility to determine salt application rates on the basis of their judgment of weather and roadway conditions. Critical bridges

and highways, such as multilane freeways, are typically treated most intensely, through higher application rates and more frequent treatment. Lower-priority streets and secondary roads are often left untreated for longer periods, or not treated at all (see Figure 2-2).

Official salt application rates for several states are listed in Table 2-1. Rates vary from state to state, although most are between 200 and 400 lb/lane-mi on high-priority highways. On medium-priority roads, coverage tends to be reduced or eliminated at night, and salt is mixed with abrasives to reduce salt use by at least 25 percent. These policies generally do not limit the frequency of application. As might be expected, northern states tend to have the highest annual loadings of salt because of their higher application frequencies. New York, Massachusetts, Michigan, New Hampshire, and Vermont report the highest annual salt loadings. Each averages more than 10 tons/lane-mi on state-maintained highways (Table 2-2).

Municipal highway agencies were not surveyed in this study. They are among the most generous users of road salt because of the emphasis placed on clearing bus lanes and commuter routes (TRB 1974). Toll authorities are also heavy salt users, because they are selling a service and do not wish to lose customers by allowing hazardous driving conditions or delays.

Storage

Salt storage facilities are usually located at highway maintenance yards as well as at other intermediate points along highways (see Figure 2-3). The location, size, and number of storage facilities often depend on the priority of the roads being treated and the incidence of special features, such as bridges and intersections that require more frequent salting.

When stored outside and exposed to precipitation, salt solution may run off and leach into surrounding soils and groundwater unless properly covered and drained. Accordingly, highway agencies increasingly store salt on impervious pads and in leakproof shelters, such as sheds, barns, or “beehive” domes that correspond to the salt pile’s angle of repose. These buildings, which often cost upwards of \$100,000 to build, can provide storage for more than 1,000 tons of salt. In recent years, some highway agencies have introduced high-capacity silos for gravity loading. Silos reduce the potential for spillage during handling while protecting the salt from exposure to moisture and humidity.



FIGURE 2-2 *Top: Primary highway. Middle: Secondary highway. Bottom: Residential street.*

TABLE 2-1 OFFICIAL SALT USE POLICIES IN VARIOUS STATES

Region and State	Summary of General Policy
New England	
Connecticut	Salt applied at 215 lb/lane-mi on multilane roads; no more than 150 lb/lane-mi on two-lane state highways
Massachusetts	Salt applied at less than 300 lb/lane-mi on state highways
New Hampshire	Salt application guideline of 250 to 300 lb/lane-mi on state highways
Middle Atlantic	
Maryland	Salt application guideline of 300 to 500 lb/lane-mi on state highways
West Virginia	Salt application guideline of 100 to 250 lb/lane-mi, usually mixed with abrasives, except in cities
Great Lakes	
Michigan	Salt applied at 225 lb/lane-mi on primary highways. Salt and sand mixtures used on lower-priority roads, depending on storm temperature and severity
Ohio	Salt applied at 200 to 300 lb/lane-mi on Interstate and primary highways; 100 to 200 lb/lane-mi, with abrasives on secondary roads; no more than 100 to 200 lb/lane-mi on low-priority roads
Wisconsin	Salt application rates of 100 to 300 lb/lane-mi recommended; additional salt use restrictions related to pavement temperature in place
Plains	
Iowa	Salt applied at 150 lb/lane-mi (mixed with sand) on Interstates and other arterials; 100 lb/lane-mi on collectors; no salt used on local roads
Kansas	Salt applied at 100 to 250 lb/lane-mi (mixed with sand) on Interstates, freeways, and other roads with 2,500+ ADT; less on roads with 750 to 2,500 ADT; no salt used on roads with < 750 ADT
West	
Colorado	Salt only with abrasives; rates not defined
-California	Salt applied at 500 lb/lane-mi on some mountain highways

NOTE: Although policies often identify an ideal salt application rate for equipment calibration, they seldom regulate the timing and frequency of applications. Application timing and frequency are typically determined by the maintenance engineer in charge during the storm. Data in the table are from states that responded to relevant questions in survey. ADT = average daily traffic.

SOURCE: TRB survey of state highway agencies.

SALT USE BY JURISDICTION AND REGION

Nationwide, there are more than 3.8 million mi of public highway and streets. Except for minor amounts of mileage on federal lands, practically all of these roads are maintained by state and local high-

TABLE 2-2 AVERAGE ANNUAL SALT LOADINGS
ON STATE HIGHWAYS WHERE SALT IS
NORMALLY APPLIED

Region and State	Average Annual Loading (tons/lane-mile)
New England	
Maine	8.0
Massachusetts	19.4
New Hampshire	16.4
Vermont	17.1
Middle Atlantic	
Delaware	9.0
Maryland	7.1
New Jersey	6.7
New York	16.6
Virginia	3.0
West Virginia	6.3
Great Lakes	
Illinois	6.6
Indiana	9.0
Michigan	12.9
Ohio	9.1
Wisconsin	9.2
Plains	
Iowa	3.8
Minnesota	5.0
Missouri	1.0
Nebraska	1.5
Oklahoma	1.5
South Dakota	1.0
Mountain and West	
Alaska	1.2
California	3.0
Idaho	0.3
Nevada	1.9
New Mexico	0.5

NOTE: Data are from only those states that responded to relevant questions in survey.

SOURCE: TRB survey of state highway agencies.

way agencies. As the data in Table 2-3 indicate, state highway agencies (including toll authorities) administer about 20 percent of this mileage, including all Interstates and virtually all other primary highways. Local governments (counties, cities, and towns) have jurisdiction over about three-quarters of all mileage, although a large share consists of low-volume secondary roads and residential streets.

Figure 2-4 shows the share of total salt usage by state, toll, county, and municipal highway agencies, derived from Salt Institute data and



FIGURE 2-3 Highway maintenance yard. *Top:* Salt hopper and spreader truck. *Bottom:* Salt storage shed.

the survey of state highway agencies conducted for this study. Because of the heavy traffic demands on primary highways, states and toll authorities are especially heavy users of salt, accounting for about one-half of all the salt used nationally. The next largest users are municipal agencies—especially large cities—which account for about 35 percent of salt use. County highway agencies account for the remaining 15 percent. Because counties are often responsible for

TABLE 2-3 ROAD MILEAGE CLASSIFIED BY FEDERAL-AID SYSTEM AND JURISDICTION
(FHWA 1989, 114-116)

Federal-Aid System Mileage						
Jurisdiction	Interstate and Other Primary			Non-Federal-Aid Mileage	Total Mileage	Percentage
	Primary	Secondary (Rural)	Urban			
State and toll	300,455	196,503	33,996	269,297	800,251	21
County	961	193,383	27,430	1,451,976	1,673,750	43
Municipal	1,560	9,269	85,534	1,116,068	1,212,431	31
Federal	470	926	75	182,888	184,359	5
Total	303,446	400,081	147,035	3,020,229	3,870,791	100

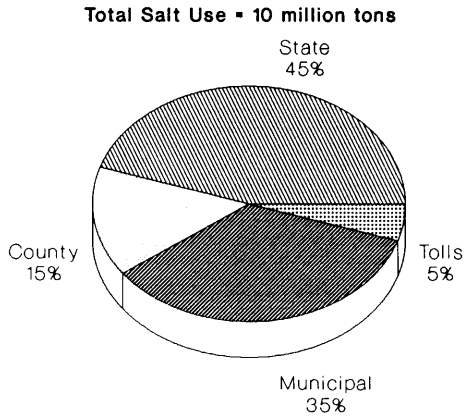


FIGURE 2-4 Salt use by jurisdiction
(source: state survey and Salt Institute).

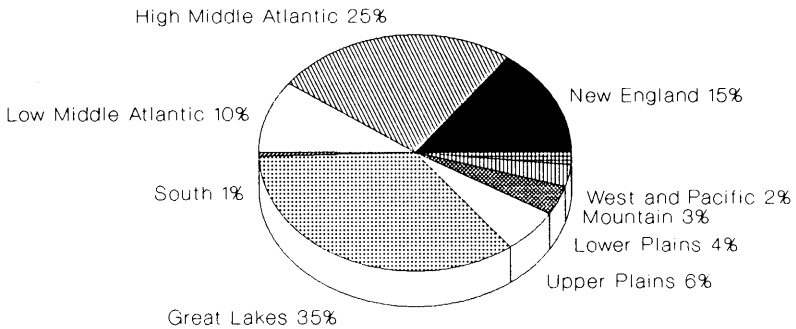


FIGURE 2-5 Salt use by region (source: state survey and Salt Institute).

clearing many miles of rural secondary roads, they frequently use less salt per lane-mile than cities and depend more on plowing and sanding.

As shown in Figure 2-5, most salt is used by states in New England, the Great Lakes, and the Middle Atlantic regions (as defined by TRB in Figure 2-6), which together account for more than 85 percent of all road salt used nationally. By comparison, states in the Plains and Mountain regions account for only 13 percent of total salt use, because they have lighter traffic demands and longer periods of cold temperatures during which salt is ineffective. These states rely more on sanding and plowing for snow and ice control. States in the Pacific and Southern regions use little road salt except at higher elevations.



FIGURE 2-6 Definition of regions.

SPENDING ON ROAD SALT

The average price of salt is approximately \$30 per ton delivered. Prices can vary from \$15 to \$40 per ton, depending on proximity to the source (e.g., salt mines) and shipping facilities. In the survey conducted for this study, state highway agencies were asked to estimate the portion of their winter maintenance budgets normally dedicated to purchasing salt and other deicing chemicals. Responses varied among states, depending on their winter conditions and demands for clear pavement. Collectively, state highway agencies spend about \$750 million per year on all aspects of winter maintenance (Figure 2-7). On the average, 20 percent of this spending, or \$150 million, is for the purchase of deicing chemicals (Figure 2-7).

The existence of thousands of county and municipal highway agencies makes it difficult to estimate salting expenditures at this jurisdictional level. Nevertheless, because municipalities and counties use about one-half of all the road salt applied each winter, these expenditures are likely to be significant. If local highway agencies collectively spend as much on salt purchases as states—which is likely because each applies about the same amount of salt—total state and local spending on salt purchases is approximately \$300 million per year (\$150 million by states + \$150 million by counties and municipalities).

This figure represents only a portion of total spending on salting operations. Related expenditures include storage, handling, and

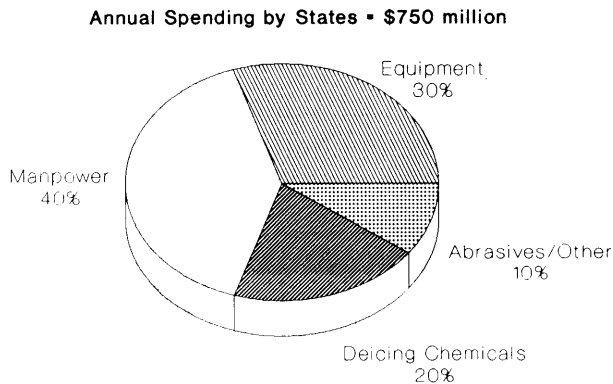


FIGURE 2-7 State spending on snow and ice control by type of expenditure (source: state survey and Salt Institute).

spreading. The New York State Department of Transportation, which accounts for about 10 percent of state-level spending on road salt, estimates that these other salt-related costs (e.g., equipment and labor for spreading, handling, and storage) average about \$25 per ton of salt applied (personal communication, Assistant Commissioner for Operations of the New York State Department of Transportation). Hence, a rough national estimate of these costs can be developed by multiplying \$25 by the 10 million tons of salt applied each winter in the United States. The result is \$250 million per year.

These estimates of salt purchase and application costs suggest that total annual spending on road salting is slightly more than \$500 million and represents about one-third of the \$1.5 billion spent on winter maintenance activities each year.

DEICING BENEFITS

Among the benefits of deicing are fewer disruptions in trucking and other commercial traffic, smaller losses in work force productivity because of absent and tardy workers, and uninterrupted provision of emergency services. Presumably, deicing also improves highway safety, although no studies have demonstrated this effect unequivocally because of the many interrelated factors found in accident statistics (TRB 1974, 8).

These benefits, which are difficult to quantify, are widely acknowledged to be valuable to society. Hence, changes in deicing policies

or practices that threaten to reduce these benefits often arouse public concern and opposition.

MANAGING ROAD SALT

Whereas salt is an effective snow- and ice-control tool, its limitations require careful management. Recognizing both the importance of highway deicing and the adverse side effects of salt, many highway agencies have tried to control salt use without sacrificing deicing effectiveness. Management improvements have focused primarily on reducing excessive salt use or waste, for example, through personnel training, more accurate and timely weather information, and better spreading equipment and techniques.

In some states computerized inventory methods that monitor salt usage by district and stockpile, and sometimes by truck, have been implemented. Combined with proper operator and supervisor training, monitoring creates incentives to eliminate unnecessary salting. Likewise, improvements in spreading equipment and weather forecasting have helped some highway agencies control salt use. For example, during the 1960s and 1970s, automatic, ground-oriented spreader controls were introduced to regulate salt discharge according to truck speed. Recently, some state and municipal highway agencies have started to contract with private weather services for storm advisories. The prediction of snow and ice conditions can shorten the lead time required to start salting operations and, therefore, reduce the amount of salt used unnecessarily when storm conditions do not develop as originally expected.

SUMMARY

Salt and other chemicals are important for highway snow and ice control. Approximately 10 million tons of salt is spread on the nation's highways each winter. Most road salt is applied in the Northeast and Midwest. Salting is heaviest on high-volume highways and city streets, where traffic demands are greatest; accordingly, many state and municipal highway agencies are heavy users of salt.

The price of road salt averages \$30 per ton. Each year, state and local highway agencies spend about \$300 million on salt purchases and another \$250 million on storage, handling, and application. To control expenditures on salting and reduce its adverse side effects, many highway agencies are reevaluating the way they use salt. Better

management practices, equipment, and spreading techniques have improved both the effectiveness and the efficiency of many salting programs.

NOTE

1. When salt dissolves in water, the freezing point is depressed in proportion to the concentration of ions in solution. Because sodium chloride is very soluble in water and yields a large number of ions per unit weight, it is especially effective as a freezing point depressant, or ice melter.

REFERENCES

ABBREVIATIONS

FHWA	Federal Highway Administration
TRB	Transportation Research Board

- FHWA. 1989. *Highway Statistics 1988*. U.S. Department of Transportation.
- TRB. 1974. *NCHRP Synthesis of Highway Practice 24: Minimizing Deicing Chemical Use*. National Research Council, Washington, D.C.

3

Effects of Road Salt on Motor Vehicles and Infrastructure



Road salt's impacts on motor vehicles and infrastructure are examined in this chapter. The focus is on three major areas: motor vehicles, bridges, and parking garages. Impacts on other infrastructure components, such as pavements, underground utilities, and road-

side objects, are also discussed, although in less detail.

MOTOR VEHICLES

Motor vehicles have suffered from more severe corrosion since the widespread introduction of road salt following World War II. Among the various side effects of salting, vehicle corrosion is by far the best known and the most extensively studied, and it is typically the single largest component in estimates of overall cost.

Corrosion damage to motor vehicles can be separated into three categories: functional, structural, and cosmetic. Functional and structural damage occur when corrosion causes a loss of operating performance or structural integrity. Examples include perforation of body panels (Figure 3-1), corrosion of brake linings, and deterioration of the frame and bumper support systems. Cosmetic corrosion affects only the appearance of the vehicle. Examples include rust staining of painted body panels and discoloration and pitting of trim metals (Baboian 1990, 1-2).



FIGURE 3-1 *Top: Structural corrosion (perforations). Bottom: Cosmetic corrosion.*

The corrosive effect of road salt on motor vehicles became apparent as early as the mid-1950s, when it was discovered that certain kinds of steel used for exterior trim were no longer resistant to localized pitting corrosion (Baboian 1981, 4–6). Although vehicle manufacturers were able to develop alternative trim metals to control this type of rusting, by the mid-1960s galvanic corrosion was occurring in body metals adjacent to trim (galvanic corrosion occurs where

dissimilar metals contact). Later, during the 1970s, rust perforations became more common in the fenders, deck lids, hoods, quarter panels, and doors of many vehicles in the Northeast and Midwest (Baboian 1981, 4-6). At about this time, unprecedented corrosion was occurring in less visible sections of the vehicle, such as frames, floor panels, exhaust systems, and fuel and brake pipes.

The proliferation of rusted-out vehicles in many northern states identified road salt as a major cause of automotive corrosion. Other contributors, however, include sea spray in coastal areas, dust-control chemicals (e.g., calcium chloride) in rural areas, and atmospheric pollutants from the burning of organic fuels. These pollutants—nitrogen oxide (NO_x) and sulfur dioxide (SO_2)—convert into acids (nitric and sulfuric acid) that cause acid rain, acid dew, and acid snow (i.e., acid deposition). Acid deposition increases the acidity (i.e., lowers the pH) of the environment, which hampers the formation of natural protective films on metal surfaces. When low-pH conditions are combined with chloride ions from road salt and sea spray, the corrosivity of the highway environment is significantly increased (Haynes and Baboian 1986).

Figure 3-2 shows that the highway environments in some regions of the country are far more corrosive than in others. The most corrosive environments are in the northeastern United States and in southern Canada, where the interactive effects of acid deposition,

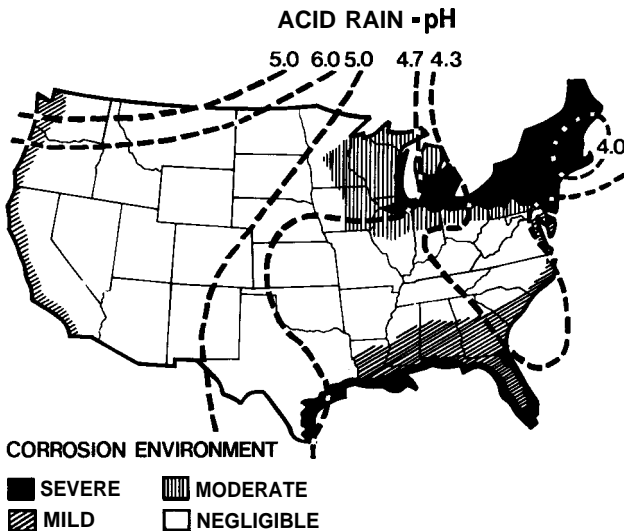


FIGURE 3-2 Corrosivity of the environment by region (Turcotte and Baboian 1985).

sea spray, calcium chloride, and road salt are greatest. Other corrosive environments are in the southern coastal areas of Florida and the Gulf Coast, where salt from sea spray, high humidities, and warm temperatures are especially conducive to corrosion.

Protection of Motor Vehicles from Corrosion

Figure 3-3 shows the benchmark years in motor vehicle corrosion superimposed on trends in salt usage and emissions of NO_x and SO_2 since World War II. The data indicate that the corrosivity of the highway environment reached its peak during the mid-1970s.

During this period, the combination of harsher operating environments and demands by motorists for vehicles that last longer forced automobile manufacturers to set up special engineering groups and testing facilities aimed at reducing the severity and frequency of corrosion. These efforts led to changes in vehicle designs, manufacturing processes, and material selection, including the use of

- More resistant and durable body metals, materials, and substrates—such as stainless steels, aluminum alloys, and plastics—and coated metals, such as clad steel, zinc alloys, and galvanized steel;
- New primer and coatings technology, such as cathodic electro-deposition primer, antichip coatings, and clearcoat paints;

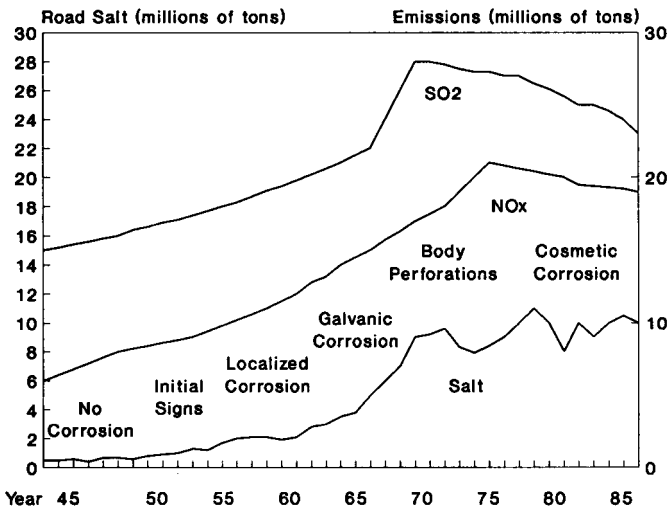


FIGURE 3-3 Road salt use and emissions of SO_2 and NO_x , 1945–1985 (Baboian 1991).

- Resin sealers for insulating body joints and crevices;
- Design configurations that reduce entrapment areas and improve the ease with which protective coatings can be applied; and
- New manufacturing technologies, such as more reliable robotics and adhesively bonded panels.

These advances and others are now used widely by most manufacturers of cars and trucks sold in the United States and Canada. Table 3-1 gives a rough approximation of the time of introduction

TABLE 3-1 APPROXIMATE TIMING OF CORROSION PROTECTION IMPROVEMENTS (Piepho et al. 1991)

Approximate Timing	Improvement
1963–1965	Two-side galvanized steel rocker panels and wheelhouses
1968	Two-side galvanized steel tailgates and use of bimetal trim
1975–1980	Immersion cathodic electrodeposition (ELPO) primer to improve perforation corrosion resistance; process implemented in most vehicle manufacturers' assembly plants by 1985
1975–1985	More one-side precoated steel products (e.g., one-side galvanized steel) on fenders, hoods, doors, and deck lids
1976	Incorporation of antichip lower body coatings
1977	One-side galvanized quarter panels
1980	Expanded use of two-side precoated steels for structural members (i.e., engine compartment rails, etc.) on new front-wheel-drive vehicles
1980	Industry provision of a 3-year/36,000-mi rust-through corrosion warranty
1982	Small crystal-size phosphate incorporated into exterior coating to improve corrosion resistance
1985	Spray phosphate systems improved and implementation of immersion phosphate systems started to improve coverage in body cavity areas for perforation resistance
1985	More two-side precoated steel products incorporated on hood, door, and deck lid inners; also, two-side precoated steel products phased into floor panels
1985–1989	Two-side galvanized steel on all major body inner and outer panels (except roof)
1987	Domestic manufacturers warranty coverage against rust-through corrosion increased to 6 to 7 years or 100,000 mi
1990	Two-side precoated products incorporated to resist rust-through corrosion

of many of these improvements. Today the stated goal of the industry is to eliminate all exterior surface rust on new vehicles for at least 5 years and perforations for at least 10 years (Piepho et al. 1991).

Perhaps the best evidence of the success of these efforts is that most manufacturers now offer long-term warranties that include rust-through coverage. Table 3-2 summarizes the corrosion warranties of various 1990 model vehicles. Of 41 major automobile makes and models, 39 include perforation coverage in their extended 1990 warranties. Coverage for most domestic cars and trucks is between 6 and 7 years or 100,000 mi. By comparison, as recently as 1980, few manufacturers were offering 3-year corrosion warranties (Piepho et al. 1991).

Cost of Corrosion Protection

Motor vehicle manufacturers have improved corrosion protection during the past 20 years for many reasons. Certainly the principal reason was the rapid increase in the use of salt and other chloride deicers (e.g., calcium chloride) during the 1960s and 1970s. Other reasons include the corrosivity of coastal environments, the aggravating effect of acid deposition, and, to a lesser degree, the summertime use of calcium chloride on dirt and gravel roads for dust control (Piepho et al. 1991).

In the late 1970s, the National Institute of Standards and Technology (formerly the National Bureau of Standards) estimated that the rust-resistant metals, special paints, and protective coatings used to control corrosion added approximately \$100 to the price of a new car purchased in 1975, or about 2 percent of the total purchase price (Bennet et al. 1978; Passaglia and Haines 1981, 13–24). As indicated in Table 3-1, improvements have been made in corrosion protection since that time. Many improvements, such as the expanded use of galvanized steel, are solely the result of efforts to improve vehicle corrosion resistance; however, several others, such as the use of plastics to improve fuel efficiency and reduce denting, are by-products of concerns other than corrosion protection.

Because many improvements were implemented for more than one reason, it is difficult to isolate costs specifically associated with corrosion protection. Manufacturers rarely maintain cost data in such an exclusive manner; even when they do, they are seldom willing to make the information public, for competitive reasons. Manufacturers contacted for this study, therefore, were asked instead to identify in general terms the major elements of corrosion protection that have

TABLE 3-2 CORROSION WARRANTY COVERAGE BY MAJOR
AUTOMOBILE MAKERS, 1990 MODELS (*Automotive News*, 1989)

Make or Model	Corrosion Coverage (years or miles)	Deductible (\$)
Domestic		
Ford truck	6/100,000	100
Mercury	6/100,000	100
Lincoln, Merkur	6/100,000	100
Buick	6/100,000	100
Chevrolet truck	6/100,000	100
Oldsmobile	6/100,000	100
Pontiac	6/100,000	100
Cadillac	6/100,000	100
Cadillac Allante	7/100,000	25
Chrysler (all)	7/100,000	100
Japan		
Acura	3/Unlimited	None
Daihatsu	3/Unlimited	None
Honda	5/Unlimited	None
Infiniti	7/Unlimited	None
Isuzu	3/Unlimited	None
Lexus	3/Unlimited	None
Mazda	6/Unlimited	None
Mitsubishi	3/Unlimited	None
Nissan	5/Unlimited	None
Subaru	6/60,000	None
Suzuki	3/Unlimited	None
Toyota	5/Unlimited	None
Korea		
Hyundai	3/Unlimited	None
France		
Peugeot	3/36,000	None
Germany		
Audi	6/Unlimited	None
BMW	6/Unlimited	None
Mercedes-Benz	4/50,000	None
Porsche	10/Unlimited	None
Volkswagen	6/Unlimited	None
Great Britain		
Aston Martin	No	None
Jaguar	6/60,000	None
Lotus	8/Unlimited	None
Range Rover	6/Unlimited	None
Rolls Royce	3/Unlimited	None
Sterling	6/Unlimited	None
Italy		
Alfa Romeo	6/60,000	None
Ferrari	No	None
Maserati	2/24,000	None
Sweden		
Saab	6/Unlimited	None
Volvo	8/Unlimited	None
Yugoslavia		
Yugo	3/Unlimited	25

increased the cost of manufacturing vehicles. In response, the cost items listed were primarily special paints, coatings, and materials. Although not exhaustive, the list includes

- ‡Precoated steels and plastics in the body;
- ‡Electrodeposition primers;
- ‡Underbody splash shields;
- ‡More extensive use of adhesives, deadeners, and sealers, including sealed electrical systems (e.g., connectors, switches, and circuits);
- ‡Special metals and coatings (such as stainless steel and aluminum) for engine and power train items, ignition components (e.g., starters and alternators), and fuel systems; and
- ‡Special bumper support systems and trim metals.

No specific cost estimates were given for individual items; instead, a range of costs was developed for the entire group. It was generally agreed that most of these systems are now used on all major vehicle makes and models sold in the United States, including imported and domestic vehicles and economy and luxury lines. Cost estimates ranged from \$250 to \$800 per vehicle for typical late-model vehicles, or about \$500 per vehicle on the average.

The \$500 figure can be multiplied by the number of new vehicles sold each year in the United States to estimate a total national cost of corrosion protection. In 1989 approximately 14.5 million new passenger vehicles were sold nationwide, including 9.9 million cars and 4.6 million vans and light trucks (mostly pickups) (MVMA 1990). These figures do not include larger trucks, trailers, buses, and recreational vehicles. Altogether, 900,000 of these vehicles-330,000 large trucks and buses, 170,000 truck trailers, and 400,000 recreational vehicles-were sold in 1989 (MVMA 1990). If \$500 is also spent on protecting these larger vehicles, the total cost of corrosion protection is about \$7.7 billion per year (\$500 x 15.4 million).

The attribution of a precise share of this cost to road salt is complicated because of the various reasons for corrosion protection besides salt. Though the expanded use of road salt has historically been the driving force behind corrosion protection, it is not clear that significant reductions in salt use today would result in substantial savings in the cost of corrosion protection. New vehicles are shipped worldwide, frequently to markets such as Europe, where the other sources of corrosion-sea spray, acid deposition, and calcium chloride-are especially severe. Also, because automotive technologies have improved and vehicle prices have increased, motorists now operate

vehicles longer and demand long-term protection from all types of corrosion and premature wear.

Estimates of savings in the cost of corrosion protection that would result from reductions in salt use vary depending on the importance ascribed to these other considerations. Estimates from motor vehicle manufacturers contacted for this study suggest that, as a practical matter, only limited reductions in the cost of corrosion protection would result, even if salt and calcium chloride were no longer used for highway deicing. The estimated savings ranged from \$125 to \$250 per vehicle, with the largest savings resulting from the reduced application of galvanized steel. To determine the savings on a national basis, a rough estimate can be developed by multiplying the \$125 to \$250 savings by the 15.4 million new cars and trucks sold each year in the United States. The estimate suggests a total cost of salt-related corrosion protection ranging from \$1.9 billion to \$3.9 billion per year.

Undoubtedly some additional corrosion-protection costs are incurred by motorists who rustproof their vehicles after purchase. Such after-market rustproofing is usually performed by the dealership or companies specializing in rustproofing applications. There is considerable controversy about whether aftermarket rustproofing is desirable and in fact deters corrosion (Piepho et al. 1991; Peterkin 1990). In this study no attempts were made to estimate these additional rustproofing costs, although the committee believes that they are fast declining in significance as manufacturer (i.e., assembly-line) rust protection improves.

Persistent Motor Vehicle Corrosion

Results from several studies indicate that assembly-line corrosion protection has been successful in reducing the severe structural corrosion that plagued cars during the 1960s and 1970s. For example, since 1985, the Automotive Corrosion and Prevention Committee of the Society of Automotive Engineers (SAE) has conducted biennial surveys of vehicles in the Detroit metropolitan area, identifying corrosion as surface rust (paint has been removed and the steel surface is rusted), blisters (bubbling of paint), or perforations (Bryant et al. 1989). To date, three surveys have been conducted, for model years 1980 through 1985 (1980, 1982, and 1984 models were surveyed at age 6; 1981, 1983, and 1985 models were surveyed at age 5).

Table 3-3 gives the share of vehicles in each survey with at least one rust defect. The table indicates that all types of body corrosion were reduced during the 1980s. For instance, the share of vehicles

TABLE 3-3 PERCENTAGE OF SURVEYED VEHICLES WITH RUST DEFECTS (Bryant et al. 1989)

	Survey 1 (1980 and 1981 Models)	Survey 2 (1982 and 1983 Models)	Survey 3 (1984 and 1985 Models)
Blisters	61	56	34
Surface rust	78	67	46
Perforations	20	8	3
Total with defects	86	80	59

with one or more perforations decreased by 85 percent, and the share of vehicles with one or more blistered panels decreased by almost one-half. Altogether, the share of 5- and 6-year-old vehicles with one or more rust defects declined from 86 percent in the first survey to 59 percent in the most recent survey.

The most important of these trends is the near elimination of perforations for at least 5 to 6 years. The SAE surveys indicate not only that the share of vehicles with perforations declined sharply but also that the number of body panels affected declined. In 1980 and 1981 models, perforations were found in 23 panels, ranging from the fenders to the roof. In 1984 and 1985 models, perforations were found in only seven panels (Bryant et al. 1989).

Reductions in cosmetic corrosion were less dramatic than declines in perforations—34 percent of vehicles surveyed had blisters and 46 percent had surface rust in 1984 and 1985 models. As mentioned previously, cosmetic corrosion often involves the trim metals. Rust “bleeding” or pitting where the trim and body metals meet (due to galvanic corrosion) is an example of cosmetic corrosion. Localized mechanical damage to the paint work and trim caused by minor accidents or stones striking the vehicle sometimes results in surface rust and paint blisters.

Without data for later-model vehicles, it is difficult to estimate the degree to which cosmetic corrosion continues to affect new cars and trucks. However, in the analysis of its survey results, SAE noted that the percentage of panels containing precoated steel on the outer surface was still small for 1984 and 1985 vehicles (the last model years in the most recent SAE survey). It anticipated that the expanded use of this material in more recent models, combined with continued improvements in phosphates, coatings, and antichip materials, will be reflected in even lower corrosion rates in future surveys (Bryant et al. 1989).

Cost of Persistent Corrosion

Murray and Ernst, in their 1976 economic analysis of the environmental impact of road salt conducted for the Environmental Protection Agency, estimated that the cost of salt-related vehicle corrosion, including corrosion protection, was about \$2 billion per year (in 1975 dollars) (Murray and Ernst 1976). Vehicle depreciation due to corrosion, which accounted for \$1.4 billion, represented the largest share of this cost. It was estimated that salt-related corrosion reduced the value of motor vehicles by as much as 1 to 2 percent per year in heavy salt-using states like New York and Massachusetts.

A simple update of Murray and Ernst's \$1.4 billion cost estimate to reflect inflation and changes in the number of vehicles would probably lead to an inaccurate depiction of current corrosion costs. Because of the progress that has been made in corrosion prevention by manufacturers, today's vehicles are less vulnerable to corrosion than vehicles built 10 to 20 years ago. Whereas cosmetic corrosion remains a significant cost for many vehicle owners, perhaps the single largest cost of corrosion is paid when purchasing new vehicles, which are equipped with more expensive corrosion-resistant materials and coatings.

Few data are available to quantify the cost of cosmetic corrosion,¹ although it remains a concern in some areas of the Northeast and Midwest, where motorists still spend money and time to prevent it and consequent losses in vehicle value. Preventive efforts include more frequent car washing and other exterior maintenance (e.g., waxing) and touching up of paint damage caused by minor accidents and stone chips. Although no reliable data are available to estimate these costs, they are likely to be significant because of the large number of vehicles in salt-using states.

A rough estimate of the magnitude of these costs can be developed on the basis of the amount that motorists in salt-using regions might be willing to spend to completely eliminate persistent cosmetic corrosion for the life of a vehicle.² As estimated in the previous section, motorists now spend between \$125 and \$250 per new vehicle for protections added by the manufacturer. This has reduced both the incidence and the severity of the structural and functional corrosion that plagued automobiles during the 1970s. If motorists in the salt-using regions of the Northeast and Midwest—where approximately 9 million new vehicles (60 percent of the total) are purchased each year (MVMA 1990)—were willing to spend an additional \$125 to \$250 per new vehicle to completely eliminate the minor forms of cosmetic corrosion that persist, this cost alone would be roughly

\$1 billion to \$2 billion per year (9 million vehicles \times \$125 to \$250 per vehicle = \$1.1 billion to \$2.2 billion).

BRIDGE DECKS

During the past 20 years, the condition of the nation's highways has received increasing attention from the public and legislators. Much of the attention has focused on premature deterioration of concrete bridge decks, caused in large part by chloride deicing salt. Whereas bridge age, traffic levels, and construction quality have also played an important role, the use of road salt has been the single most important factor in deck repair and maintenance problems.

The effect of salt on bridge decks is well understood. During the 1950s and 1960s, thousands of decks were constructed, many of them on newly constructed Interstates, using cast-in-place concrete heavily reinforced with steel bars. The upper steel bars were designed to be positioned approximately 2 in. below the concrete surface in most of the decks (TRB 1984, 107). Soon after construction, however, many decks developed pores or fine cracks from the deck surface to the reinforcement bars (rebars). Under low- or no-salt conditions, rebars are normally protected from corrosion by the highly alkaline environment of the concrete, which forms a natural protective film of ferrous oxide on the steel surface. However, when chloride ions from road salt penetrate through the pores and cracks, the protective film is disrupted and corrosion can begin.

Corrosion of steel in concrete can occur in several forms. The most damaging form is termed macrocell corrosion, in which large areas of the steel (often the top rebar mat) become corroding anodes, and other areas (usually the bottom rebar mat) become noncorroding cathodes. The rebars act as an electrical pathway, conducting electrons from the anodic to the cathodic areas. The chloride ions and water molecules act as an electrolyte, completing the electrical circuit. As the steel corrodes, the rust product expands, exerting pressure on the surrounding concrete and causing it to crack and disbond. Eventually this process leads to spalling, or potholing, of the deck surface (Figure 3-4). In turn, the potholes provide access to additional salt and moisture, which aggravates the destructive processes already caused by freeze-thaw, vibrations, and impact loadings from traffic (TRB 1984, 109).

Rusting of rebars is usually considered detrimental because it degrades the ride quality of the deck. Safety is also a concern. Because bridge decks often have limited maneuvering room and sometimes

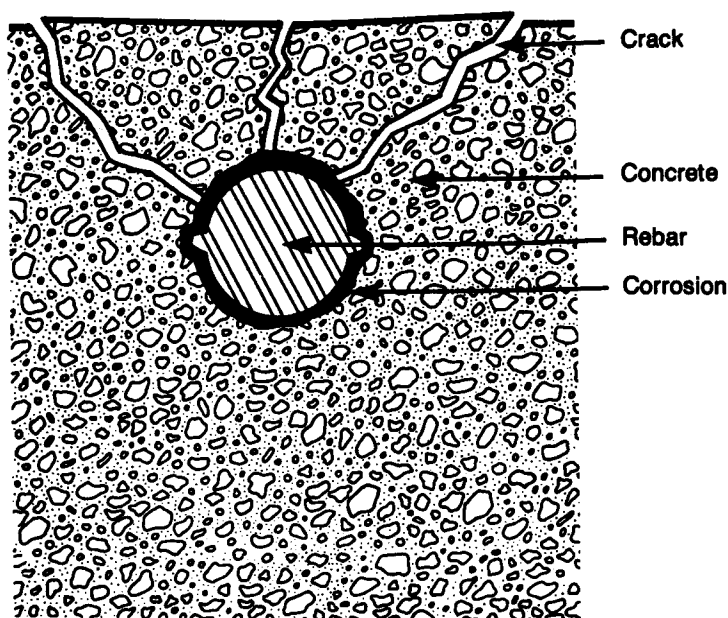


FIGURE 3-4 Damage caused by rebar corrosion.

lack full shoulders, even minor irregularities and potholes can result in hazards that require prompt repair.

Bridge Deck Repair and Rehabilitation

Conventional methods of deck repair range from patching of individual potholes during early stages of deterioration to complete deck replacement if potholes and patches cover a large portion of the deck. Because of its low cost, patching is the most common repair, although its effectiveness is usually only temporary (Figure 3-5). To provide longer-lasting repair, the damaged concrete must be replaced with new concrete and special waterproof membranes or sealers that prevent further intrusion of salt and moisture. Such partial restoration, however, is seldom completely successful in halting the corrosion process, because unrestored sections often begin to corrode after the deck has been repaired.

A disadvantage of partial deck restoration is that signs of corrosion, such as potholes, may not become evident until well after a large portion of the deck has become critically contaminated with chlorides. Once this critical, or threshold, contamination level has been



FIGURE 3-5 Patching of a severely contaminated concrete deck.

reached, deck deterioration usually continues, regardless of the subsequent use of salt or noncorrosive deicers. In many northern cities, where road salt is applied frequently and in large quantities, unprotected decks reach the threshold contamination level within 10 to 15 years after construction.

Unless they are rehabilitated (and protected), continued deterioration is probably inevitable for thousands of decks in northern

states that are already severely damaged or critically contaminated with chloride.³

Repair and Rehabilitation Costs

According to the National Bridge Inventory, about 55 percent of concrete decks in the United States are in sound condition and not already critically contaminated with chlorides. Presumably, however, some of them will become contaminated and damaged by continued salting. Table 3-4 gives the percentage of undamaged decks by region. In particular, the heavy salt-using regions of the Northeast and Upper Midwest have a noticeably smaller share of undamaged decks than do other regions. For instance, among 11- to 20-year-old decks, only 75 percent are undamaged, compared with about 85 percent in low-salt regions. Moreover, among 21- to 30-year-old decks, only about 45 to 60 percent are undamaged, compared with about 65 to 75 percent elsewhere.

Regional variations in deck condition are useful reference points for estimating the effect of continued salting on future deck repair costs. For example, in salt-using states of the Northeast, Midwest, and Mountain regions, approximately 60,000 new decks (built during the past 20 years) are undamaged and vulnerable to chloride contamination from continued salting (Table 3-5). On the basis of historical rates of deck deterioration in these regions, one would expect approximately 15 percent, or 10,000, to become damaged during the next 10 years because of continued salting. If the lower rates of deck

TABLE 3-4 DETERIORATION RATES OF DECKS BY REGION

Region	Percentage of Bridge Decks in Sound Condition After		
	1–10 years	11–20 years	21–30 years
New England	93	77	47
Upper Middle Atlantic	94	74	47
Lower Middle Atlantic	91	72	58
Great Lakes	92	80	58
Upper Plains	90	70	64
Lower Plains	95	88	74
Mountain	91	83	64
South, Pacific, and West ^a	92	85	74

^aExcluding Florida, Alaska, and Hawaii, which have exceptional environments.

SOURCE: Computer analysis of National Bridge Inventory file.

TABLE 3-5 ESTIMATED NUMBER OF DECKS THAT WILL BE DAMAGED BY CONTINUED SALTING DURING NEXT 10 YEARS

Region	Current No. of Undamaged Decks ^a (1)	No. of Undamaged Decks Damaged During Next 10 Years		Difference (4) = (2) - (3)	Average Deck Surface Area (ft ²) (5)	Total Deck Surface Area (ft ²) (6) = (4) × (5)
		Continued Road Salting (2)	Absence of Road Salt ^b (3)			
New England	2,100	500	200	300	7,600	2.3 million
Middle Atlantic (Upper and Lower)	22,000	4,200	1,000	3,200	7,300	23.3 million
Great Lakes Plains	20,400	4,000	1,700	2,300	7,100	16.3 million
(Upper only ^c)	11,900	1,000	200	800	6,800	5.4 million
Mountain	<u>6,200</u>	<u>800</u>	<u>500</u>	<u>300</u>	6,600	<u>2.0 million</u>
Total	62,600	10,500	3,600	6,900	7,100	49.3 million

^aIncludes only the population of bridges that are less than 20 years old, because these bridges may not already be contaminated with chlorides.

^bCalculated by applying historical deck deterioration rates in the South and West to the existing population of undamaged decks in salt-using regions.

^cLower Plains states have deterioration rates similar to those of the South and West and therefore were excluded from the analysis.

SOURCE: Computer analysis of National Bridge Inventory file.

deterioration in the low-salt regions of the South and West are used instead, one would expect only about 5 percent, or approximately 3,000, to be damaged (Table 3-5).

This rough calculation suggests that about 7,000 decks (10,000 – 3,000) will become damaged during the next 10 years because of continued salting. As a practical matter, however, future deck damage will probably be less severe than past rates of deterioration suggest, mainly because of recent advances in bridge deck protection (discussed in the next section). Because of these advances, it is reasonable to assume that 7,000 is the high end of the range, and that about half this number is the low end.

To estimate the average annual cost of repairing damaged decks, it can be assumed for simplicity that about 1 in 10, or 350 to 700, will need to be rehabilitated each year during the 10-year period. The typical surface area of a deck is 7,000 ft² (Table 3-5). Multiplication of this average by 350 to 700 decks yields between 2.5 million and 5 million ft² that will need to be rehabilitated each year. According to estimates by the California and New York State highway departments, the average cost of rehabilitating a concrete deck, whereby the concrete is replaced and the rebars are cleaned, is between \$20/ft² and \$40/ft² (personal communications, Structures Division, New York State Department of Transportation and Office of Transportation Materials and Research, California Department of Transportation). Multiplication of this cost range by the 2.5 million to 5 million ft² that would need to be repaired each year results in a repair cost of between \$50 million and \$200 million per year.

Bridge Deck Protection

The premature deterioration of concrete decks during the past 20 years challenged highway agencies not only to save the thousands of decks that were already critically contaminated with chloride but also to design and construct more durable decks that are resistant to salt-induced corrosion. Because bridge decks are complex systems, the challenge involved many elements of the deck, ranging from improved deck drainage and joint sealants to special deck overlays that impede migration of chlorides into the concrete.

Since 1984, FHWA has required protections on all new federal-aid bridges in salt-using states. The types of protections used, however, vary among states, depending on individual needs and the performance and cost of each type. In the survey of state highway agencies conducted for this study, 40 of 48 responding states reported

that they routinely use some type of protective system on bridges built where road salt is used. By far the most common is epoxy-coated reinforcing steel, the use of which is standard in 25 states. Other types of protection range from waterproof membranes and special deck overlays to additional concrete cover over the reinforcing steel. Of the 25 states that routinely use epoxy-coated steel, 18 combine it with a waterproof membrane, additional concrete cover, a special deck overlay, or other protective systems.

The cost of installing and maintaining various protective systems has been studied by the National Cooperative Highway Research Program (NCHRP) (Babaei and Hawkins 1987). According to that study, epoxy-coated steel combined with a special deck overlay is the most expensive, costing about \$5.50/ft² more to install than a basic unprotected deck (Table 3-6). The least expensive is an additional 2 in. of concrete cover, which adds about \$2.15/ft² to new deck construction costs. The average incremental cost of these alternatives is about \$4/ft² more than a basic concrete deck.

This average is useful for quantifying the future cost of protecting newly constructed decks. An analysis of National Bridge Inventory file data indicates that between 3,000 and 4,000 new decks, with a total surface area of 20 million to 30 million ft², are constructed each year in salt-using regions of the United States (where deck protection is mandatory). Given an average incremental cost of deck protection of \$4/ft², the total cost is \$75 million to \$125 million per year (\$4/ft²

TABLE 3-6 INCREMENTAL COST OF VARIOUS BRIDGE DECK PROTECTION SYSTEMS (Babaei and Hawkins 1987, 53)

Alternative	Additional Cost ^a (\$/ft ²)
1. Basic deck (no protection)	—
Single Protection	
2. Additional 2 in. of concrete cover	2.15
3. Epoxy-coated top rebar mat	2.60
4. 1.5 in. of latex or 2.0 in. of low-slump concrete cover	4.85
5. Additional 0.5 in. of concrete cover, plus asphaltic concrete membrane	4.40
Double Protection	
6. Alternative 3, plus epoxy-coated bottom rebar mat	3.25
7. Alternative 4, plus epoxy-coated top mat	5.50
8. Alternative 5, plus epoxy-coated top mat	5.20
Average	4.00

^aOriginal 1986 cost estimates were updated for inflation.

cost \times 20 million to 30 million ft² of deck surface, rounded to the nearest \$25 million).

OTHER BRIDGE COMPONENTS

Much of the research that has been devoted to developing methods for repairing and protecting bridges from salt damage has focused on concrete bridge decks. Road salt, however, also contributes to the deterioration of other bridge components, including grid decks, joints, drainage systems, and elements of the bridge structural system that are exposed to salt from leaky decks, faulty drainage, and splash and spray from the roadway.

Grid Decks, Joints, and Drainage Systems

In addition to its use in reinforced concrete, steel is the primary material in various other components of the deck system, including grid decks, joint devices, and drainage systems. These components are vulnerable to corrosion from road salt, but numerous other factors affect their durability as well.

Most steel decks are made of grid mesh, which accounts for about 5 percent of all deck surfaces. Grid decks provide drainage of water, dirt, debris, and road salt through the grid openings. Most older grid decks have a framework of steel beams and stringers to support the mesh panels. Salt-laden snow, mud, sand, and other debris tracked onto the deck often drop onto the supporting structures, causing corrosion. Accordingly, grid decks and their supports must be regularly cleaned and painted as a precaution against rusting, which can be exacerbated by road salt (AASHTO 1976, 35–46).

Joint devices, likewise, require vigilant maintenance. Joints allow for movements of the deck caused by traffic loadings and thermal expansion and contraction. They are often made of metal formed into finger bars or plates and are therefore susceptible to rusting, especially if they are improperly sealed and become clogged with debris containing moisture and salt (AASHTO 1976, 89–126). Rusted joints that do not perform properly can generate stresses on the deck that result in pavement fracturing or cracking of the bridge approach slab. Road salt is therefore a factor that can affect joint corrosion and durability.

Like joints, deck drainage systems require frequent maintenance. The drainage system is vital to the bridge because it eliminates trap-

ped or ponded water, which can be hazardous to traffic and contribute to deterioration of the bridge understructure. Most drainage systems use metal pipes that funnel water from the deck to the ground. Poor drainage is usually caused by debris clogging the pipes (AASHTO 1976, 61–66). When drainage systems fail, backed-up water, which may be contaminated with salt, can corrode the pipes and reach the bridge's structural system.

Structural Components

Bridge structural components vary according to bridge design, but usually include superstructure members, such as girders, stringers, and arches, which support vertical loads; substructure members, such as abutments and piers, which transmit loads from the superstructure to the ground; and bearings, which transmit loads from the superstructure to the substructure while allowing the bridge to undergo necessary movements without harmful stress. Most bridge structural elements are made of steel, reinforced concrete, or prestressed concrete, which, if exposed to road salt, are vulnerable to corrosion damage.

Bearings

Bearings serve an important function by allowing structural elements to undergo stress movements without damage. Bearings are often located where the superstructure (e.g., girders) and the substructure (e.g., pile caps) meet. Most bearing devices are constructed of steel, neoprene, bronze, or a combination of these materials (AASHTO 1976, 171–182). The steel portions of bearings are normally protected by paint or galvanization. However, sand, dirt, debris, and road salt often accumulate around the bearings, which can encourage corrosion and “freezing” of the bearing, especially if the protective system is poorly maintained.

Steel Framing and Supports

Corrosion is a problem for most steel frames and supports (AASHTO 1976, 127–199). The corrosive action of atmospheric pollutants, sea spray, and moisture all make regular cleaning and painting of steel necessary in most regions of the country. Corrosion of steel is usually

detected before it becomes a serious hazard. Repairs are made by removing the rust and applying a protective paint or coating or by replacing the rusted steel section with metal plating. Corrosion is accelerated by dirt, debris, and moisture that become trapped in pockets and crevices created by the framing and connection of steel members. The addition of salt to this environment increases the potential for more frequent and severe corrosion, especially if bridge cleaning and painting are lax.

Concrete Support Structures

Road salt is frequently associated with deterioration of bridge structural elements made of reinforced concrete (AASHTO 1976, 61–66). The problem is similar to that of concrete decks; chlorides from road salt, along with moisture, migrate to the rebars, inducing corrosion and causing the surrounding concrete to crack (Figure 3-6). Reinforced concrete box beams, stringers, pile caps, and support columns are among the structural elements affected. Leaky joints, poor drainage, and splash and spray from traffic provide avenues for salt access.

Because road salt is not applied directly to these elements, salt damage takes longer to be identified and is generally not as extensive as salt-induced damage to decks. However, because of cramped working conditions and the need for falsework and scaffolding, repair of even minor damage can be difficult and expensive. Research is under way to develop less costly repair and rehabilitation treatments, such as electrochemical chloride removal (Broomfield and Jawed 1990; Manning and Schell 1987; Manning and Pianca 1991). These treatments, along with greater attention to deck drainage and corrosion protection (such as epoxy-coated steel) should help reduce the severity and incidence of this damage. Nevertheless, because rehabilitation of the structural components of one long-span bridge can cost several million dollars (personal communication, Structure Division, New York State Department of Transportation), the total cost of salt-related damage is likely to be quite high.

Prestressed Concrete

There is some evidence that long-term exposure to road salt can damage prestressed concrete used for structural support. Prestressing improves the strength of bridge structural components by the ten-



FIGURE 3-6 Concrete spalling on bridge structure.

sioning of steel strands in the concrete. Because several prestressed segments can be strung together with minimal intermediate support, this design is popular for long-span bridges crossing stretches of rough terrain, bodies of water, and congested urban areas. Because the steel strands are vital to structural integrity, the consequences of corrosion are far greater than corrosion of rebars.

According to the National Bridge Inventory, there are about 25,000 prestressed bridges in the United States, accounting for about 5 percent of all bridges. To date, surveys of the condition of these bridges have found few corrosion-related problems. More than 12,000 prestressed concrete bridges were built in the United States between 1951 and 1966. According to an NCHRP study, highway agencies in 14 states that collectively contain more than half of these bridges report no widespread problems (Perenchio et al. 1989, 5). In addition, a survey conducted by the American Concrete Institute found that of more than 30 million strands installed between 1950 and 1977, only 200 were affected by corrosion, usually due to corrosive environments involving seawater, poor design details, or faulty construction (Shupack 1978). Prestressed concrete has been known to fracture and fail due to hydrogen embrittlement and stress corrosion, although reported instances of this type of damage are rare and usually unrelated to road salt use (Perenchio et al. 1989, 5).

The sudden collapse of a 30-year-old prestressed concrete bridge in the United Kingdom in 1985, which was attributed to road salt-induced corrosion, renewed debate about the potential for salt-induced corrosion of prestressed concrete bridges (Woodward 1989). Of particular concern is that corrosion of prestressing strands may take several decades to occur, because the strands are often embedded in grout or special ducts. Most prestressed concrete bridges are relatively new, constructed during the past 35 years. Corrosion protection in many of these structures was provided by the use of high-quality construction materials and additional concrete cover. Because of the potentially catastrophic consequences of corrosion, most highway agencies now take extra precautions by coating and protecting the strands, ducts, and anchoring hardware in new bridges (Perenchio et al. 1989, 2–3).

Because of the uncertain effect of road salt on prestressed concrete bridges, cost projections would be speculative. The only cost that can clearly be associated with salt use is that of corrosion protection and detection activities. However, should significant corrosion of

prestressed concrete bridges eventually be discovered, the total cost would be considerably higher.

Summary of Impacts on Other Bridge Components

In addition to decks, components of bridges that are vulnerable to salt damage include concrete supports, steel framing, bearings, and joint devices. The effects of salt on these components are frequently obscured by durability and maintenance factors unrelated to salt use. Salt can reach these components because of leaky decks, faulty drainage, and splash and spray from the roadway. Compared with deck damage, however, deterioration of other bridge components can be more expensive and difficult to repair, especially if it involves structural support elements. Although there is not enough information available to estimate costs reliably, the committee believes that collectively they are as large as deck costs and, as a rough approximation, fall within the same range, \$125 million to \$325 million per year.

OTHER HIGHWAY COMPONENTS

Road salt is clearly a principal factor in bridge durability. Its impacts on other highway system components, including pavements, drainage systems, and roadside fixtures and appurtenances, are more incremental and difficult to isolate.

Pavements

Pavements (both concrete and asphalt) are the single most expensive component of the highway system, accounting for about one-fifth of all highway expenditures (TRB 1984, 64). In recent years, interest in reducing these expenditures has generated considerable research aimed at improving pavement designs, materials, and maintenance practices. However, the impact of road salt is not an area of major concern or research.

Perhaps the best-known effect of road salt on pavements is its aggravating effect on surface scaling, or flaking, in poor-quality portland cement concrete. When improperly cured, overfinished, or inadequately entrained with air—whereby microscopic air bubbles are mixed in with the concrete—concrete pavement is vulnerable to stress damage caused by trapped moisture that freezes and expands.

Road salt can exacerbate this problem, both by increasing freeze-thaw cycles and by forming expanding crystals in the concrete. This effect is no longer a serious concern for most highway agencies, however, because air entrainment has been a standard construction practice for many years.

A more practical concern is the performance and durability of pavement expansion joints. Expansion joints are constructed in concrete pavement to control stresses. The joints themselves, however, require considerable maintenance. Cracks in jointed pavements are sometimes caused by corrosion of steel dowels that are installed in the joint. The purpose of these devices is to transfer loads across joints while allowing the joints to open and close freely in response to slab movements. When these devices corrode, however, they may restrain joint movement, resulting in slab faulting and cracking. The use of road salt is a factor considered by highway agencies when they select metals and coatings used in joint devices (TRB 1979, 12). Yet, because joints are sometimes unsealed and exposed to numerous other corrosion sources—such as moisture, dirt, and debris—it is difficult to attribute a portion of this damage to road salt.

The corrosion of the reinforcing steel sometimes used in concrete pavements is another potential effect of salt. According to the Concrete Reinforcing Steel Institute, there are about 30,000 lane-mi of reinforced pavement in the United States, mostly on freeways and other heavily traveled highways (Concrete Reinforcing Steel Institute 1983, 1). Reinforcing steel eliminates the need for joint devices and provides additional concrete tensile strength. Like decks, reinforced pavements are susceptible to spalling and cracking caused by rebar corrosion. Overall, however, the extent and severity of this damage does not approach that of bridge decks, and the general condition of these pavements is thought to be well within the normal bounds for pavements serving high volumes of traffic (TRB 1979). During the 1970s, several incidents of severe spalling of pavements were linked to the use of deicing salt in Minnesota (TRB 1979, 10). Few serious problems have been reported since that time, although some northern states (e.g., Wisconsin) are using epoxy-coated rebars in new concrete pavements.

Highway Drainage Systems

Some of the salt spread on highways is washed through highway drainage and storm sewer systems, consisting of reinforced concrete culverts, metal pipes, catch basins, grates, manhole covers, curbs,

and gutters. Because drainage systems account for about 10 percent of highway construction and maintenance expenditures and are important to highway operations and safety, their performance and durability are critical (TRB 1978, 3).

A deteriorating drainage system can be difficult and expensive to repair. Treatments, such as retrofitting coatings and linings to pipes, are often costly and conflict with the original design objectives of the structure (TRB 1978, 23). Hence, as a precaution, new culvert pipes are often equipped with thicker walls, galvanized coatings, and protective paving materials. In addition, to prevent scaling and cracking of curbs and grate spacers due to freeze-thaw effects, air-entrained concrete and stone are used in new construction.

Although high concentrations of road salt can enter highway drainage systems after storms, the water flow usually causes dilution. High chloride concentrations over a long period may accelerate the corrosion of drainage pipes by interfering with the formation of natural protective films on pipe surfaces and by increasing the conductivity of draining water (Bednar 1989, 70). In addition, salt may contribute to scaling and cracking in improperly cured or finished concrete grout, curbs, and grate spacers by aggravating freeze-thaw effects. In general, however, salt is not considered a significant factor affecting the durability of drainage systems. During the past 30 years, several states have studied the performance of highway drainage systems. The studies have led highway agencies to conclude that the factors with the greatest effect on durability are soil type, water alkalinity and hardness, traffic stress and vibration, silting, road settlement, erosion, and water abrasion (TRB 1979; Bednar 1989, 70–71).

Highway Fixtures and Appurtenances

Signposts, light columns, circuitry in traffic signals, guardrails, wire fencing, retaining walls and noise barriers, as well as their concrete bases and connection hardware, are vulnerable to damage from road salt. Many highway fixtures and appurtenances are specially painted or constructed with corrosion-resistant materials. For example, wiring and fences are made of galvanized steel, light and sign supports are constructed of aluminum alloy tubing and anchored with stainless steel bolts, and guardrails are often painted with zinc-rich primer (American Public Works Association 1985). However, in general, the factors with the most effect on the maintenance and replacement schedules of these components are normal wear, vehicle collisions,

vandalism, obsolescence, and vibrations from traffic (American Public Works Association 1985).

Sidewalks and Driveways

Public and private sidewalks and driveways may be exposed to salt from direct application, splash and spray from traffic, pedestrian and vehicle tracking, and runoff from salt-laden snowbanks. If the concrete used is poorly finished or improperly air entrained, scaling may be accelerated by frequent exposure to salt (because of freeze-thaw effects). Most damage to sidewalks and driveways, however, stems from settlement, erosion, growth of vegetation, and traffic stress (American Public Works Association 1985).

Snow- and Ice-Control Equipment

Salt spreaders, hoppers, loaders, snowplows, blowers, and other equipment used for highway snow and ice control are susceptible to rusting because of road salt, especially if cleaning and maintenance are neglected. Because of differences in equipment usage and maintenance practices, the extent of salt damage varies by jurisdiction. As estimated in Chapter 2, nearly \$500 million is spent annually by highway agencies to purchase, maintain, and operate snow- and ice-control equipment; hence, if even a small percentage is related to the effects of salt-induced corrosion, the total cost could be several million dollars per year.

Summary of Impacts on Other Highway Components

The durability of most highway components is affected by a number of factors, usually related to the quality of original construction, maintenance practices, and the environment in which they are located. Road salt is one of these factors, but not the most important. On the basis of the limited evidence available, the committee believes that, as a group, salt-related costs of damage to highway components are sizable but probably an order of magnitude smaller than bridge costs—totaling less than \$100 million per year.

PARKING GARAGES

According to estimates from Census Bureau data, there are about 10,000 multilevel parking garages in the United States. About half are located in the salt-using regions of the Northeast and Midwest.⁴ Although they vary in type from freestanding structures to multilevel decks integrated into other buildings, most are made of either cast-in-place or precast reinforced concrete. Many were built during the 1960s and 1970s, when concerns about salt-related corrosion were minimal. Most were originally designed for 40-year service lives without major deck repairs or renovation. During the past 20 years, however, hundreds have been deteriorating prematurely.

During the winter months, road salt is dropped by parked cars onto the slab flooring of parking garages. Over time, salt and moisture seep into the slabs, reach the reinforcing steel, and induce corrosion. The process is similar to that of bridge deck corrosion; the rust product expands and exerts pressure, causing the surrounding concrete to crack. The cracks allow more moisture, salt, and oxygen to reach the embedded steel, further accelerating the destructive process. Untreated, some of these cracks may expand to form delaminations that can lead to progressive structural weakening and losses in serviceability. In addition, leaky joints and poor drainage provide avenues for more salt and moisture, damaging walls, electrical conduits, and concrete beams and support columns.

Parking Garage Repair and Rehabilitation

Because of several decades of salting, hundreds of parking structures have had to undergo major repair and rehabilitation during the past 20 years. The most common method of repair is simple patching and surface sealing, which is often combined with waterproof membranes. This treatment may postpone the need for additional repairs for 2 to 6 years (Table 3-7). By the time numerous potholes appear, however, the garage deck is usually critically contaminated with salt, so continued corrosion and deterioration are inevitable unless more extensive repairs are made (American Concrete Institute 1985). Longer-lasting repairs usually involve removal of the unsound concrete, cleaning of the reinforcing steel, and placement of a modified concrete that reduces moisture penetration. This method of repair is about twice as expensive as simple patching but may postpone the need for more extensive repair by 10 years or more (Table 3-7).

TABLE 3-7 INCREMENTAL COST OF VARIOUS PARKING STRUCTURE REPAIRS (Tighe and Van Volkinburg 1989, 71)

Repair Option	Cost (\$/ft ²)	Added Structural Life (years)
Patching and sealing	1.00	2–5
Patching and membranes	3.25	4–6
Conventional concrete removal and replacement with high-performance overlay	7.50	10–12

Other methods of repair include cathodic protection and the injection of epoxy or other penetrants into cracks to serve as sealers.

Repair and Rehabilitation Costs

According to estimates derived from Census Bureau data, about 5,000 parking structures are located in the Northeast and Midwest (U.S. Department of Commerce 1989). Many of them, especially older ones built during the 1950s and 1960s, have already undergone major rehabilitation because of corrosion damage. Many newer structures built during the 1980s are equipped with state-of-the-art protections that should limit corrosion damage.

Although it is difficult to project how many of these 5,000 garages will be damaged by continued salting, the most likely candidates are those built during the 1970s. Many garages built during that decade lack protective systems and have not yet been restored. In recent years many have started to deteriorate. Information is not available on the number of parking garages in salt-using regions that were built during that period, although the committee estimates that the number is between 500 and 1,500 (about $\frac{1}{10}$ to $\frac{1}{3}$ of the 5,000 total garages in the Northeast and Midwest).

If an average of 1 in 10 of these structures becomes severely damaged each year during the next 10 years, 50 to 150 will need to be rehabilitated each year. The average cost of the most common method of rehabilitation—concrete removal, cleaning of rebars, and a high-performance overlay—is about \$7.50/ft² (Table 3-7). The average surface area of a parking garage is 150,000 ft² (500 stalls \times 300 ft² per stall) (personal communication with consulting engineers, Elgard Corporation and Parking Market Research Company). Hence, the average cost of repairing one damaged parking structure is approx-

imately \$1 million ($\$7.50 \times 150,000 \text{ ft}^2$), and the cost of repairing 50 to 150 per year is \$50 million to \$150 million.

Parking Garage Protection

In recent years, as corrosion damage has become more evident, most new parking garages have been built with structural features and protective systems intended to reduce chloride- and weather-related damage. About 90 percent of new structures are built with one or more protective systems (Table 3-8). Conventional methods—used in three-quarters of new structures—are penetrating sealers, membranes, and other surface treatments. Other methods include galvanized or epoxy-coated reinforcing steel, additional concrete cover, and corrosion-inhibiting concrete additives. In addition, more attention is paid to design and construction details, such as sloped floors for better drainage and proper concrete curing and finishing.

Protection Costs

According to estimates by the Parking Market Research Company (a reporting service for the parking garage construction industry), protective systems increase the cost of constructing a new parking garage by about 1 to 1.5 percent, or by about \$100,000 to \$150,000 per garage on the average (Parking Market Research Company 1987). Approximately 200 garages are built each year in the northeastern and midwestern United States, resulting in annual spending for protection of approximately \$25 million ($200 \times \$100,000$ to $\$150,000$).

TABLE 3-8 TYPES OF WEATHER PROTECTION SYSTEMS USED IN NEW PARKING STRUCTURES (Parking Market Research Company 1987)

Protective System	Percent of New Structures ^a
Sealers, membranes, and other surface treatments	77
Coated reinforcing steel	13
Additional concrete cover	11
Corrosion-inhibiting concrete additives	7

^aColumn totals more than 100 percent because many structures have two or more protective systems.

UNDERGROUND OBJECTS

Corrosion damage to utility lines, pipelines, and steel storage tanks buried under or alongside highways is sometimes attributed to the use of road salt, especially in urban areas, which have a high density of underground utility lines and heavy salt usage. Altogether, the United States has about 2 million mi of natural gas and water distribution lines and service laterals (TRB 1988, 14). In many large cities electric and telephone distribution lines are buried underground; the total mileage of these systems is unknown.

Perhaps the best-publicized claims of salt damage to underground utilities have been made by Consolidated Edison Company of New York City. For more than 20 years it has blamed salt for occasional short circuits and burnouts of underground electric power transformers, switches, and service cables that are not well insulated (personal communication, Senior Research Engineer, Consolidated Edison Company; Murray and Ernst 1976). Apart from New York City, few occurrences of salt-related damage to underground utilities and pipelines have been reported. During the 1970s, the Illinois Bell Telephone Company reported corrosive failures of underground cables and transformers near where road salt was used (Kroon 1976). During the 1960s and more recently, higher-than-normal chloride concentrations in soils, possibly due to deicing salts, were identified as a possible cause of corrosion failures in some iron water mains in Milwaukee, Wisconsin (Hamman and Mantes 1966; Gummow 1984).

Utility industry associations contacted for this study reported few incidents of salt-related damage. The only problem reported by the American Gas Association was that road salt can aggravate corrosion of pipeline hangers and other anchoring hardware on bridge crossings (personal communication, Engineering Services Representative, American Gas Association). According to the Electric Power Research Institute, most buried electric distribution and service cables are well insulated, which reduces the likelihood of both short circuits (due to salt in water acting as an electrolyte) and corrosion damage. It was noted, however, that road salt may contribute to short-circuiting of older transformers, switches, and secondary lines that are not well insulated (personal communication, Engineering Representative, Electric Power Research Institute). The American Water Works Association did not know of any direct relationship between road salt and corrosion damage. It noted that road salt may be one of many factors contributing to a changing soil environment (e.g., higher chloride levels), which in recent years has caused many water companies to convert to corrosion-resistant materials for some pipe and

valve components (e.g., stainless steel bolting on valves) (personal communication, American Water Works Association).

Finally, another potentially important, although uncertain, side effect of road salt concerns fuel storage tanks buried under gas station service yards. During the past 10 years in particular, the corrosion of these tanks has become a major environmental and public health concern. Thousands have been discovered leaking into surrounding soil, contaminating groundwater. According to the Steel Tank Institute, cleanup and removal of a single leaking tank can cost several hundred thousand dollars (personal communication, Steel Tank Institute). Because road salt is continually tracked into gas station service areas, it is considered one of many factors contributing to this problem, although it is not possible to isolate the specific effect.

The impact of road salt on underground objects, especially on a national basis, is difficult to quantify because of lack of information. Corrosion is second to excavation damage as the leading cause of failures in pipelines; pipeline operators and utility companies spend millions of dollars each year monitoring corrosion, installing cathodic protection, applying rustproof coatings, and repairing corrosion damage (TRB 1988). Expenditures on the cleanup and removal of corroding and leaking underground storage tanks amount to hundreds of millions of dollars each year (personal communication, Steel Tank Institute). Hence, although it is not possible to isolate the effects of road salt on these costs, even minor contributions could have major cost implications.

ROADSIDE OBJECTS

In addition to its potentially adverse effect on underground objects, road salt may negatively affect certain nonhighway objects located aboveground on the roadside. For instance, salt may contribute to the corrosion and degradation of bronze statues, monuments, and copper roofing that are exposed to traffic-generated splash, spray, and mist. The severity and extent of damage depend largely on prevailing local conditions, such as the degree of salt usage, the number of roadside objects, and the presence of other corrosion factors. Corrosion damage can be expensive and difficult to repair for many of these objects, especially those with historic or artistic significance. Available data are insufficient to isolate the effect of road salt on these costs.

SUMMARY OF COSTS

Great strides have been made in the past 10 years in reducing the adverse side effects of salting by protecting motor vehicles and infrastructure from corrosion. Advances are continuing, and the outlook for further reductions in damage is promising. Collectively, however, the indirect cost of salting remains high, because of both salt protection costs and persistent salt damages.

The committee's estimates of annual salt costs associated with motor vehicles and infrastructure are summarized in Table 3-9. The reliability of these estimates varies by cost item. Some cost items, such as motor vehicle protection and bridge deck damage, can be quantified reliably on the basis of available data (Category I). Summation of the more reliable cost estimates suggests a minimum indirect cost of salting between \$2 billion and \$4.5 billion per year. Several other cost items for which limited supporting data are avail-

TABLE 3-9 SUMMARY OF ANNUAL COSTS FOR MOTOR VEHICLES AND INFRASTRUCTURE FROM CONTINUED SALTING

Cost Item	Annual Cost (\$ millions)
Category I (Data Reliable and Complete)	
Motor vehicle corrosion protection	1,900–3,900
Bridge decks	125–325
Parking structures	75–175
Total	2,100–4,400
Category II (Estimates Based on Committee Judgment)	
Motor vehicle corrosion damage	1,000–2,000 ^a
Bridge nondeck components	125–325
Other highway components	100 ^b
Total ^c	1,200–2,400
Category III (No Reliable Data Available)	
Roadside objects	N.A.
Underground objects	N.A.
Use costs ^d	N.A.

NOTE: N.A. = not available.

^aFrom an illustration in Chapter 3 of the potential magnitude of these costs if car buyers in salt-using states are willing to spend an additional \$125 to \$250 per new car (the cost of existing salt protection) to eliminate persistent cosmetic corrosion.

^bCost totals less than \$100 million, assuming it is an order of magnitude smaller than total bridge costs.

^cRounded to nearest \$100 million.

^dExamples include user costs associated with salt damage and repair to bridge decks and parking garages.

able, such as persistent motor vehicle corrosion and damage to highway components, can be approximated only on the basis of committee judgment and conjecture to provide a rough sense of scale (Category II). Inclusion of these items results in a less precise, although more complete, cost range of about \$3.5 billion to \$7 billion per year.

Because of lack of data, salt's additional impacts on bridge and parking garage users, underground utilities (and utility users), and other roadside objects cannot be similarly quantified. These costs are likely to be important in individual situations.

NOTES

1. As a method of approximating this cost, the committee initially considered comparing used-car prices in different regions of the country. Presumably, price depreciation is greatest in heavy salt-using regions, where cosmetic corrosion is more severe. For several reasons, however, the committee was not confident that this method of analysis would yield reliable results. For instance, factors besides corrosion can affect used-car price variations among regions, including differences in vehicle maintenance practices, driver skills, weather and driving conditions, and income levels. Also, used cars are often moved between regions for resale, which tends to reduce regional price differences. Because controlling for these factors would require a sensitive econometric model and wide range of information that is not readily available, the committee decided not to pursue this approach.
2. This approach requires surmising how much new-vehicle buyers would be willing to pay to prevent salt-related corrosion for the life of a new vehicle. Presumably, most new-vehicle buyers would be willing to spend at least as much on corrosion protection (at purchase) as the present-value cost of all future corrosion damage and preventive maintenance that would be avoided. Hence, by estimating "willingness-to-pay" for corrosion protection, the dollar cost of corrosion damage is determined implicitly.
3. Some treatments are available to counteract corrosion, but they are not widely used for various technical and economic reasons. One such treatment is cathodic protection, which can slow corrosion by providing a uniform current flow throughout the reinforcing steel. Cathodic protection is usually accomplished by impressing a direct electrical current between the reinforcing steel and an inert anode. Although cathodic protection has been used for years on buried steel pipelines, its use is less straightforward when applied to steel in concrete, which is inferior to soil as a conducting medium. Currently, only 200 to 300 bridge decks in the United States are cathodically protected (Swiat and Rog 1987).

Another promising, although still experimental, treatment for controlling corrosion of contaminated decks is electrochemical chloride removal, in which a direct electrical current is impressed between the reinforcing steel and a temporary anode placed on the concrete surface. The impressed current, which is about 100 times' greater than the current used for cathodic protection, draws the chloride ions away from the reinforcing steel. Whereas the concept of electrochemical chloride removal is not new, recent work in Europe has led to successful techniques that are now being studied by several highway

agencies as a possible concrete rehabilitation treatment for the future (Broomfield and Jawed 1990; Manning and Pianca 1991).

4. A precise count of the number of parking structures in the United States is not available. Parking garage construction consultants contacted for this study estimated that the number is close to 10,000 (personal communication, consulting engineers, Elgard Corporation). According to Census Bureau data, 3,145 parking structures were operated by private parking companies in 1987 (U.S. Department of Commerce 1989). This figure does not include parking structures operated by municipalities or institutions primarily engaged in other activities (e.g., hospitals and department stores). According to a survey conducted by the Parking Market Research Company, private parking companies accounted for about one-third of new parking garages built or planned between 1986 and 1989 (Parking Market Research Company 1987). If the 3,145 garages reported by the Census Bureau account for only one-third of all parking structures, the total number of structures is 9,435 ($3,145 \times 3$), or roughly 10,000. According to Census Bureau data, approximately half of all parking structures—about 5,000—are located in the Northeast and Midwest, where road salt use is heaviest.

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ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
FWHA	Federal Highway Administration
MVMA	Motor Vehicle Manufacturers Association
NCHRP	National Cooperative Highway Research Program
SAE	Society of Automotive Engineers
SHRP	Strategic Highway Research Program
TRB	Transportation Research Board

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4

Road Salt Impacts on the Environment



Hundreds of reports have been written during the past three decades documenting the impact of road salt on the environment. The literature clearly indicates that the impacts can be significant but depend on a wide range of factors unique to each site.

The emphasis of this chapter is on summarizing what is known about road salt's environmental effects on the basis of these reports. The effects discussed are those most frequently cited in the literature—damage to roadside vegetation, water, and soil. Because the significance of each effect varies by location, in the absence of detailed information it is not possible to quantify costs on a national basis. Instead, to help illustrate the discussion and provide some perspective on cost, the chapter concludes with several hypothetical cases.

VEGETATION

The adverse effects of salt on roadside vegetation have been known for some time. Incidents of vegetation injury were first reported in Minnesota during the 1950s, when trees along city boulevards started to show signs of salt-related decline (French 1959). At about this time the New Hampshire Highway Department reported the death and removal of nearly 14,000 trees along 3,700 mi of salt-treated highways (Sucoff 1975).

Investigations of salt's impact on vegetation were conducted during the 1960s and 1970s in New Hampshire, Minnesota, Michigan, and several other snowbelt states, usually in response to concerns about damage to roadside trees (Lacasse and Rich 1964; Sucoff 1975; Bowers and Hesterberg 1976; Scharpf and Srago 1975). More recently, damage to trees and other roadside vegetation has been investigated in the Adirondack region in New York and the Lake Tahoe basin of California and Nevada (Gidley 1990; Fleck et al. 1988; Kliejunas et al. 1989; Nevada Department of Transportation 1990).

Whereas most of these investigations have been site specific, they have helped reveal the general mechanisms of salt injury to vegetation. Roadside trees and other vegetation are injured by salt primarily through two mechanisms: (a) increased salt concentrations in soil and soil water, which can result in salt absorption through roots, and (b) salt accumulation on foliage and branches due to splash and spray. Vegetation that has been injured by salt exhibits clear physiological symptoms, including leaf scorch, late summer coloration, early fall defoliation, reduced shoot growth, and dying twigs and branches in the crown. Injury due to salt is typified first by inhibition of general growth, followed by specific injuries to foliage and limbs, and, in some cases, plant death (Jones et al. 1986).

Concentrations of either sodium or chloride can be harmful to vegetation. Threshold levels for each vary by species and in relation to other environmental stresses and conditions. Factors such as temperature, light, humidity, wind, soil texture and drainage, precipitation, plant size, salt exposure, species tolerance, and especially water availability contribute to the degree of salt injury (Nevada Department of Transportation 1990). Other factors with an effect are vehicle exhaust emissions, wind exposure, and alterations in drainage patterns due to highway construction. In general, chloride is thought to be more harmful than sodium to vegetation. When absorbed through roots, chloride tends to accumulate in plant tissues over a long period of time, causing osmotic stress, which can lead to dehydration injury typical of drought (e.g., leaf scorch or tip burn) (Bowers and Hesterberg 1976; Walton 1969). Sodium's impact on vegetation is less direct, although high concentrations can alter soil structure and permeability, which can be detrimental to plant growth, as discussed later in this chapter.

Salt particles themselves can also adversely affect vegetation. High concentrations of salt particles in soil can damage root systems and inhibit root growth (Nevada Department of Transportation 1990; Eggens 1980). Salt particles may be deposited on foliage and twigs due to splash and spray from traffic and wind. Physical breakdown

of the plant may result because of the added weight of the salt deposit, but tissue damage due to local dehydration is more common (Wilcox 1984; Bowers and Hesterberg 1976; Foster and Maun 1978). Broad trees and shrubs with high surface areas are especially susceptible to damage from salt splash and spray (Smith 1970). Damage increases with the amount of salt applied and with traffic volume and speed; it decreases rapidly with distance from the roadway (Lacasse and Rich 1964; Sucoff 1975). Splash and spray damage is evidenced by injury restricted to the windward side of the plant or portions not normally covered by snow and ice during the winter (Sauer 1967; Hofstra and Hall 1971).

The slope of the roadside is a key factor in determining where salt reaches vegetation, either from splash and spray or root absorption. For example, in a study of the Lake Tahoe basin, the percentages of salt-exposed trees were compared on steep, gentle, flat, uphill, and downhill slopes (Nevada Department of Transportation 1990). The mean percentage of salt-exposed trees on the steepest downhill slopes was significantly greater than on all other slope types; 50 percent of the trees on the steepest downhill slopes were affected by salt. The zone of salt exposure in that study ranged from 17 ft from the pavement edge for flat slopes to approximately 53 ft for steep downhill slopes. Overall, the mean zone of exposure was 36 ft from the pavement edge for downhill slopes and 22 ft for uphill slopes. Similarly, a study conducted in the Sierra Nevada by the California Department of Transportation indicated that vegetation was most likely to be exposed to road salt within 10 ft upslope and 40 ft downslope of Interstate highways (Gidley 1990).

The correlation between salt exposure and roadside slope is widely discussed in the literature (Lacasse and Rich 1964; Sucoff 1975). Exposure distances also vary according to other factors, such as drainage, traffic levels, wind and weather conditions, and the intensity and frequency of salt treatments. For example, the Connecticut Department of Transportation found that airborne salt traveled as far as 300 ft from the roadway under heavy traffic conditions on Interstate and other primary highways (Connecticut Department of Transportation, personal communication). Also, salt spray can be transported downwind for distances greater than 500 ft under high wind conditions (Chung 1981).

Even when exposed to high salt concentrations, the degree of vegetation damage depends on many other factors. The Nevada Department of Transportation has identified the following factors as especially important (Nevada Department of Transportation 1990):

- **Temperature:** The effects of salt are compounded by higher temperatures, which cause increased dehydration through foliage, faster movement of salt to the plant, and increased salt absorption through roots.

- **Light:** Exposure to direct light increases the rate of dehydration.

- **Humidity:** High humidity lowers the rate of dehydration and, therefore, helps alleviate water stress.

- **Wind:** Exposure to wind may increase the rate of dehydration. In general, more damage is found on the windward side of trees than elsewhere.

- **Soil water:** As salinity increases, the soil water available to plants decreases. High concentration of salt in soil can cause more injury when soil water is limited because of below-normal precipitation.

- **Soil texture and drainage:** The ability of soil to retain salt is partially determined by soil texture and drainage characteristics. For example, coarse-textured soils are quickly leached of salt, and steep slopes may not absorb salt because of rapid runoff.

- **Precipitation:** Rain and other precipitation are a transport mechanism for salt. Rainfall can flush salt deposits from foliage and dilute salt solutions in soil water. On the other hand, precipitation can transport salts, via surface runoff, to roadside soils.

The type and condition of roadside vegetation also affect the degree of salt damage. Different tree and shrub species have varying tolerances for salt, and within species, plant maturity and size affect salt tolerance. The sensitivity of various groups and species of vegetation is summarized in the following sections.

Deciduous and Coniferous Trees

Generally, the trees that are most sensitive to salt are broad-leaved species, such as linden, black walnut, and sugar and red maples (Murray and Ernst 1976). In roadside maples, levels of chloride greater than 0.5 percent dry weight of plant tissue have been highly correlated with moderate damage to leaves (e.g., discoloration) (Hall et al. 1972), and levels of 1 to 2 percent have been associated with severe leaf burn, defoliation, and even plant death (Allison 1964). Among conifers, chloride concentrations of 1 percent in the needles of red and white pine have been associated with extensive plant injury (Hofstra and Hall 1971).

Salt-resistant tree species include oak, birch, white ash, and Scotch and jack pine (Shortle and Rich 1970; Hofstra and Hall 1971). These

trees tend to retain less chloride as a percentage of tissue weight. Table 4-1 gives 12 species of salt-tolerant trees and 10 species of intolerant trees (Shortle and Rich 1970). Other listings of the relative salt tolerances of trees and other woody species are provided in the literature (e.g., Sucoff 1975; Sauer 1967), and a near-complete listing—for more than 450 trees and shrubs—is contained in *Economic Impacts of Highway Snow and Ice Control* (FHWA 1977).

For salt-sensitive trees, distance from the roadway helps explain salt damage. A study in Ontario found that trees within 35 m (about 100 ft) of the pavement showed growth reduction trends, whereas trees more than 75 m (200 ft) away did not (Hall et al. 1972). A study of the effect of sodium chloride on ponderosa pine and green-leaf manzanita in the Sierra Nevada found few damaged trees beyond 40 ft of the roadway (Interstate highways) (Gidley 1990). Another study found that chloride concentrations in maple tissue from New Hampshire roadsides were above normal only within 30 ft of the pavement edge (Lacasse and Rich 1964).

In response to concerns about increasing tree mortality in the Sierra Nevada, state highway agencies in California and Nevada studied a 64-mi corridor of highway in the Lake Tahoe basin (Nevada Department of Transportation 1990). The corridor, which extended 100 ft on both sides of the roadway, had approximately 150,000 trees (2,400 trees per mile), of which an estimated 10 to 15 percent (20,000) were affected to some degree by salt. This estimate was based on 206 sample woodlots that contained 5,450 trees. Of the sampled trees, 55 percent did not exhibit any signs of salt injury, drought, disease, insects, or mechanical damage. Of the 10 to 15 percent of trees affected by salt, about one-third showed signs of other types of injury or disease as well.

Because similar estimates are not available for a wide range of circumstances and conditions, it is difficult to generalize about salt damage to roadside trees. However, the literature indicates certain conditions that are most likely to result in problems. Densely wooded areas located downhill and within 40 to 60 ft of heavily traveled, salt-treated highways are primary candidates for salt-related damage.

Orchard Trees

Some fruit trees are especially sensitive to aerial spray and soil concentrations of salt (Hofstra and Lumis 1975; Harper 1946). Hofstra and Lumis investigated injury to apple trees in orchards located along Ontario highways treated with salt. They found the suppression of

TABLE 4-1 SALT TOLERANCE IN COMMON ROADSIDE TREES (Shortle and Rich 1970)

Tree Species	No. of Trees Rated	Percent in Each Injury Class			Percent Chloride	
		Healthy	Slightly Injured	Moderate to Severe	Roadside Trees	Woodlot Trees
Salt Tolerant						
Red oak	108	100	0	0	0.02	0.02
White oak	70	100	0	0	0.14	0.06
Red cedar	29	100	0	0	0.06	0.09
Black locust	26	100	0	0	0.32	0.09
Quaking aspen	26	100	0	0	0.78	0.12
Black birch	19	100	0	0	0.84	0.09
Paper birch	3	100	0	0	1.15	0.01
Gray birch	78	96	4	0	0.27	0.05
Yellow birch	19	95	5	0	0.78	0.10
Black cherry	36	92	8	0	0.09	0.02
White ash	154	92	8	0	0.40	0.10
Large-toothed aspen	9	89	11	0	0.66	0.10
Salt Intolerant						
Basswood	54	57	41	2	0.90	0.18
Shagbark hickory	107	67	23	10	1.27	0.27
American elm	112	62	22	16	1.13	0.38
Red maple	282	63	11	26	1.01	0.36
White pine	155	43	29	28	0.58	0.24
Ironwood	26	43	27	30	0.94	0.34
Hemlock	80	1	62	37	0.68	0.50
Sugar maple	115	27	23	50	0.84	0.24
Speckled alder	117	31	8	61	0.91	0.54
Red pine	140	9	15	76	1.08	0.06

flowering and the dieback of shoots that are associated with increased levels of sodium and chloride in twigs. Chloride accumulation in tree tissues was found to increase from February to April, during the peak salting season. In follow-up spray tests, damage to these types of trees was associated with chloride values of 0.2 to 0.5 percent of dry leaf weight. Brown et al. found that foliage injury appeared when chloride concentrations reached 1 percent dry weight for apricot and peach, 0.6 percent for prune and plum, and 1.2 to 1.8 percent for almond (Brown et al. 1952).

Some orchard owners have sought compensation from highway agencies for salt-related damage to fruit trees and crops. In a case in Ontario, two fruit growers claimed substantially reduced crop quality and yields because of salt applied to highways adjacent to their fields. In response, the Ontario Ministry of Highways compiled data on 168 orchards in southern Ontario through a survey questionnaire (Ontario Ministry of Highways 1967). The survey results indicated a correlation between damage to trees and wind direction, presence of a downsloping roadside, and high traffic volumes. It was concluded that a number of different contaminants could have been responsible for the damage—including road dust and dirt, oil deposits, vehicle exhaust emissions, and road salt—which neither confirmed nor repudiated that road salt was a factor. However, the Ontario Supreme Court ruled that the plaintiffs were entitled to recover damages from the government for the losses that were ostensibly due to salting practices (Ontario Supreme Court 1981).

Shrubs, Ground Cover, and Grasses

Excessive sodium and chloride exposure can also cause droughtlike symptoms in some shrubs and ground cover because of osmotic stress and water imbalance. Certain shrubs and ground cover are less tolerant of salt than others. Hibiscus shrubs, for instance, have poor tolerance of salt. They exhibit leaf burn and defoliation at fairly low concentrations of chloride in tissue (Bernstein et al. 1972). Shrubs and ground cover generally demonstrating good to high tolerance of salt include rosemary, natal plums, and bougainvilleas (Bernstein et al. 1972).

Turf grasses, in general, can withstand and survive considerable salt exposure, especially from salt spray. Grasses tend to be more resilient than trees and shrubs. Some grasses are more tolerant than others; for instance, bent grasses are less tolerant than bluegrass, which is a preferred grass for midwestern and eastern roadside land-

scaping (Cordukes 1968). Dehydration injury has been observed in some grass sods when exposed to high salt concentrations in soil, though such concentrations are seldom generated by highway deicing (Eggens 1980; Holmes 1961).

Wetland Vegetation

Alterations in plant communities in roadside bogs were reported near an uncovered salt storage pile in Indiana (Wilcox 1986). High salt runoff from the pile caused the loss of many endemic plants, such as blueberry and huckleberry. After the storage problem was corrected, many of the endemic plants returned to the bog within 4 years.

Except for this incident, runoff of road salt into wetlands is rarely identified in the literature as a problem. Salt tolerance in many prominent wetlands species, such as cattails, is high (Anderson 1977). Currently, the state of Massachusetts is applying an alternative to salt (calcium magnesium acetate) on a new section of highway adjacent to a cranberry bog. The policy stems from a state agency ruling that prohibits the use of chloride deicers on this section of highway, although the impact of road salt runoff on cranberry bogs has not been established (Massachusetts Department of Public Works, personal communication).

Measures To Prevent Vegetation Damage

Concerns about salt injury to roadside vegetation have led to a number of recommendations for minimizing road salt's effects, including the following (Hanes et al. 1970):

- Use salt-tolerant grasses near pavements;
 - Place sensitive woody plants as far from the roadways as possible;
 - Use salt-tolerant woody plants in essential near-roadway plantings (e.g., for erosion, noise, and glare control);
 - Use spray-tolerant plant species in areas subject to salt spray;
 - Avoid planting sites near heavy runoff areas, such as low slopes;
- and
- Place shallow ditches along roadsides to divert salt runoff from sensitive trees.

For many situations, however, redesign of roadsides is not practical. As a result, most highway agencies are faced with three options: acceptance of some salt-related damage to roadside vegetation, discontinuance or restriction of salt treatments in especially sensitive areas, or use of a deicing substitute with fewer side effects than salt (Hanes et al. 1970).

SURFACE WATER

In most parts of the country, fresh water contains low salt concentrations. Average chloride concentrations in freshwater lakes and rivers are 0 to 100 mg/L, and most concentrations are lower than 20 mg/L (Goldman and Horne 1983). However, salt and its components, sodium and chloride, can access fresh water through numerous sources. Seawater, which contains chloride concentrations of about 20 000 mg/L (Table 4-2), is a potential source of salt in fresh

TABLE 4-2 TYPICAL CHLORIDE CONCENTRATIONS
IN SOURCES OF WATER (Hanes et al. 1970)

Type of Water	Chloride Concentration (mg/L)
Rainwater	0–2
Upland surface water	0–12
Unpolluted river water	0–15
Springwater	0–25
Deep well water	0–50
Sewage water	70–500
Seawater	20 000

waters in coastal areas. Other sources are natural salt deposits, brines from oil and gas fields, household sewage, agricultural chemicals, and industrial waste (Hanes et al. 1970). During the past 30 years, salt runoff from highways, especially from salt storage facilities, has been identified as a source of salt in surface water. In recent years greater attention to salt storage practices has reduced the incidence of storage-related contamination; hence, this section focuses on highway surface runoff as a source of surface water contamination.

During and after storms and during spring melts, highway runoff may contain high concentrations of sodium and chloride. For instance, chloride concentrations higher than 10 000 mg/L have been reported in Ontario and Wisconsin during early spring thaws near large roadside snowbanks (Kronis 1978; Schraufnagel 1965). Ordinarily, however, even high concentrations of salt are quickly diluted when they

enter larger water systems. For example, Schraufnagel found chloride concentrations higher than 10 000 mg/L in spring runoff in Wisconsin, yet the maximum concentration in adjacent surface waters was only 45 mg/L (Schraufnagel 1965). As discussed in the following sections, this dilution effect varies by size and type of surface water.

Rivers and Streams

Correlations have been established linking road salt to elevated chloride concentrations in surface waters. The correlation is weakest for large rivers because of the large dilution factor associated with river volume (Scott 1976; Hawkins 1971; Walker and Wood 1973; Van de Voorde et al. 1973; Ralston and Hamilton 1978). Generally, smaller roadside streams and creeks are more likely to be affected. The magnitude of the impact depends on factors such as water flow, salting intensity, precipitation, type of highway drainage system, topography, and natural drainage patterns (Scott 1980; Champagne 1977; Wulkowicz and Saleem 1974).

A study of 28 streams in the Sierra Nevada found noticeably higher chloride concentrations at stream locations that crossed salt-treated highways than at upstream locations far from the highway (e.g., 50 to 70 mg/L versus 0 to 10 mg/L) (Hoffman et al. 1981). Studies of small creeks and drainage basins in Illinois and New York found maximum chloride concentrations that exceeded 500 mg/L during late winter and early spring thaws (Bubeck et al. 1971; Walker and Wood 1973; Diment et al. 1973; Hawkins and Judd 1972; Scott 1979). In contrast, Hutchinson found that the effect of road salt on sodium and chloride levels in seven Maine streams and rivers was compensated for by the increased flow associated with the spring snowmelt (Hutchinson 1970).

Like most studies of salt's impacts on the environment, investigations of stream and river impacts have been site specific, and findings have been largely circumstantial. Evidence, however, consistently points toward the general conclusion that salt concentrations diminish rapidly as water volume and distance from the roadway increase. Hence, small streams and creeks running adjacent to heavily traveled, salt-treated highways are more likely to be affected by salt runoff than larger streams and rivers, which are likely to experience comparatively minor impacts.

Lakes and Ponds

Some correlation has been found between salting activity and higher sodium and chloride concentrations in lakes and ponds. However, unlike small streams and creeks, ponds and lakes are often recharged by a large and varied watershed (including groundwater), which increases dilution and complicates efforts to identify specific sources of chloride and sodium. As an example, Hutchinson found that chloride concentrations in small roadside ponds in Maine varied from less than 5 to more than 100 mg/L, often for reasons only partially related to road salt usage (Hutchinson 1966).

Determination of sources of sodium and chloride concentrations in larger lakes is even more complicated because of the potential for many industrial and residential sources of sodium and chloride, particularly in urban areas. For example, chloride concentrations have been rising in the Great Lakes since the beginning of the century; however, it is not clear how these increases have been affected by road salt, because the upward trend began long before the widespread use of deicing chemicals (Bowden 1981; Kenaga 1978; Fromme 1971). Meanwhile, Lake George in New York and Lake Tahoe in California and Nevada, large rural lakes in regions with heavy salt use (e.g., to clear roads for ski resorts), have shown little change in sodium and chloride concentrations over time (Lipka and Aulenbach 1976; Goldman, unpublished data).

Aquatic Life

In general, the impacts of salt concentrations from highway deicing on water life are thought to be minor. Whereas high and sustained chloride concentrations in surface waters (more than 1000 mg/L) have been linked to growth changes in some plankton (Stewart 1974; Antonyan and Pinevich 1967), field studies indicate that such high concentrations are uncommon (Goldman and Hoffman 1975; Kersey 1981; Molles 1980). The extreme chloride concentrations that are harmful to fish (400 to 12 000 mg/L) are rarely generated by highway deicing (Schraufnagel 1973; Jones et al. 1986).

In theory, a salt load to a lake or pond will sink to the bottom because of its higher density. This effect can reduce water circulation and reaeration in lower depths, which can lead to loss of dissolved oxygen and mortality of organisms inhabiting this region (Hawkins

and Judd 1972). Prolonged periods of reduced oxygen can result in increased nutrient loading at the stream or lake bottom, which could increase spring and summer algal growth, which, in turn, may further deplete dissolved oxygen. In the literature, however, few incidents of this extreme effect have been reported, the most notable being Irondequoit Bay near Rochester, New York (Bubeck et al. 1971).

Groundwater

Highway salt enters groundwater in several ways. Runoff from highways can flow from the pavement into unlined ditches and infiltrate surrounding soil. Road salt applied during snowstorms is generally plowed off the roadway and paved shoulder. When the resulting snowbanks melt, the meltwater, together with the dissolved salt, can migrate through soil and move to the water table. Groundwater supplies nearly half of the U.S. population with household water (Bouwer 1978). Hence, the potential for road salt to contaminate groundwater has become a concern in several parts of the country, especially in the Northeast, where salt use is heavy. Because this concern is related primarily to salt in drinking water and its impact on health, discussion of effects on groundwater is reserved for the following chapter.

SOIL

Road salt's impacts on vegetation and water are linked to its movement through soil, which is one reason to consider salt's impact on soil. Soil also merits separate attention because it affects other factors, such as roadside stability.

The infiltration of salt into soil depends on a variety of site-specific factors. Because most salt is plowed or splashed off the pavement, the highest salt concentrations are usually found near the shoulders of the roadway (Murray and Ernst 1976). When salt is transported by highway runoff, the transport distance usually depends on local features and conditions, such as the slope of the roadside, direction of drainage, type of highway drainage system, soil type, vegetative cover, presence of snow and ice, and precipitation (Colwill et al. 1982).

The downward transport of salt through soil is often slow and dependent on the drainage, or infiltration, characteristics of the soil.

Sand, gravel, and coarse-textured soil allow fast infiltration, whereas clay and fine-textured soil slow infiltration (Jones et al. 1986). Chloride moves through soil faster than sodium. Chloride ions are negatively charged and are repelled by similarly charged clay and other soil particles. Sodium ions, which are positive, undergo ion-exchange with other positive ions in soil particles, which results in the retention of higher percentages of sodium in the soil, especially if infiltration is slow (Jones et al. 1986; Murray and Ernst 1976; Maryland Department of Transportation 1987).

Studies of sodium and chloride levels in soil generally indicate that the greatest concentrations are found within 5 to 10 ft of the pavement edge (Berthouex and Prior 1968). However, depending on local conditions, impact areas can be more extensive. For instance, Hofstra and Smith reported higher-than-background concentrations of sodium and chloride as far as 30 ft from the roadway (Hofstra and Smith 1984). High concentrations of sodium and chloride are not usually found at depths below 1 to 3 ft (Prior and Berthouex 1967; Hutchinson and Olson 1967; Hanes et al. 1970). In some cases all concentrations of sodium and chloride are leached from the soil by late spring or summer (Berthouex and Prior 1968); in other cases leaching is slower and sodium may accumulate for several years (Hsu 1984; Hutchinson and Olson 1967).

The soil science literature has documented the impact of sodium chloride on soil structure. Sodium accumulation, in particular, can bring about undesirable properties in soil, including diminished permeability and higher alkalinity. A complete loss of permeability is unlikely, because highway runoff and precipitation often facilitate sodium leaching. Nevertheless, sodium can increase the compactness of clay soils and cause the dispersion of suspended particles in the soil that are important for improving percolation and aeration (Jones et al. 1986). Sodium can also increase soil alkalinity by reducing the exchange capacity of the soil, thereby reducing levels of calcium, magnesium, and other nutrients that are important for soil fertility and vegetation growth.

Chloride is generally considered less detrimental than sodium to soil. There is some evidence from laboratory experiments that chloride passing through soil contributes to mobilization (to groundwater) of some heavy metals, such as cadmium, zinc, and lead (Hahne and Kroontje 1973; Amrehein and Strong 1990), but field evidence of this effect is limited. A recent field study in southern Ontario found that concentrations of heavy metals in groundwater beneath

roadside soils were similar to those in nonhighway locations (Pilon and Howard 1987).

HYPOTHETICAL SITES

Figure 4-1 shows a flow diagram of the major pathways of road salt in the environment identified in the literature. The diagram indicates that though it may be convenient to study the impacts of salt on one aspect of the environment in isolation (e.g., roadside trees or water quality), their ramifications on the entire roadside ecosystem must also be considered. Examples include the potential for increased soil erosion following the death of vegetation, the ability of soils to trap and flush salts, and the consequences for local vegetation and water.

To illustrate these impacts and their interactions under varying conditions and circumstances, several hypothetical sites are discussed in this section. Though they are generalized—derived from composites of many actual studies—they provide insight into how road salt interacts with the roadside environment. The sites are identified on the hypothetical road map in Figure 4-2. They include

1. Deciduous, coniferous, or mixed forest trees adjacent to a four- or six-lane Interstate or other primary highway;
2. Deciduous, coniferous, or mixed forest trees adjacent to a two-lane rural or secondary highway;
3. An Interstate or other primary highway through a forested corridor that drains into a stream and lake;
4. Shrub and grass vegetation adjacent to an Interstate or other primary highway with forest in the background;
5. A maintenance-yard adjacent to a highway bordered by a residential area and forest trees and shrubs; and
6. An orchard adjacent to an Interstate or other primary highway.

For each hypothetical site, the type of impact and extent of potential damage is characterized, and the cost of mitigating the damage is approximated whenever possible. The characterizations are based in part on information provided by a survey of state highway agency officials and follow-up interviews. The cost estimates are intended to add perspective; however, they are not universally applicable and do not take into account costs that are more difficult to quantify, such as losses in roadside aesthetics. The latter costs are affected by

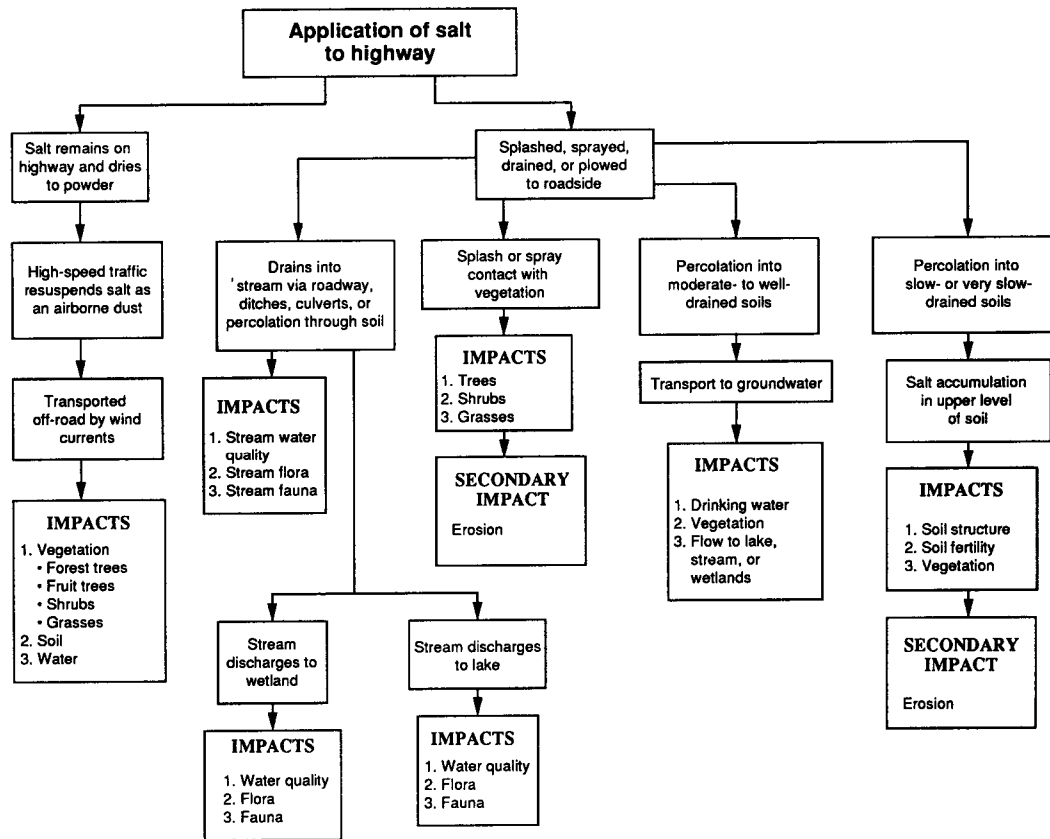


FIGURE 4-1 Flow diagram summarizing possible pathways of road salt movement through the environment.

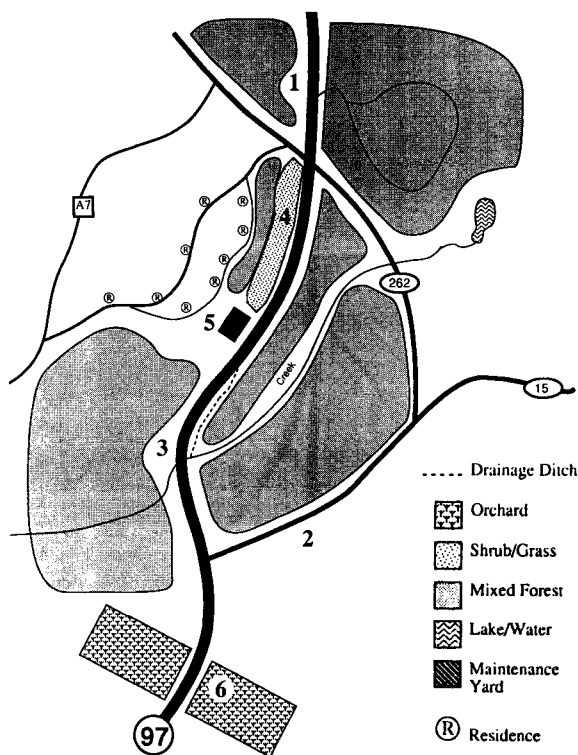


FIGURE 4-2 Map of six hypothetical sites.

local circumstances (e.g., tourist value and public concern) that cannot be depicted with this methodology.

Site 1

Site 1 consists of deciduous, coniferous, or mixed forest trees adjacent to a 1-mi section of a four-lane Interstate or other primary highway with open drainage (i.e., no special drainage system to divert runoff). Traffic speeds range from 50 to 65 mph, increasing the potential for airborne salt spray. A flat topography with no significant potential for roadside erosion is assumed. As a consequence, salt damage is confined primarily to forest trees and, to a lesser extent, soils. Annual salt loadings on the highway exceed 10 tons per lane-mi, as is common on many primary highways in New England, New York, and the Great Lakes region.

Forest Trees

Salt damage to roadside trees typically occurs as a result of (a) salt accumulation in soil, (b) traffic splash and direct contact with plowed snow containing salt, and (c) airborne salt spray or mist. The case study literature and information from discussions with state highway agencies indicate that damage from each of these causes is typically limited to within 40, 60, and 100 ft of the pavement edge, respectively. Within each zone, salt exposure declines rapidly with distance from the roadway. A standard corridor of forest, which is 1 mi long and 100 ft wide on both sides of the highway, can have from 1,250 to 3,500 trees per mile, according to estimates provided by highway agencies. The actual number of trees depends on the setback or tree-clear zone. In many states, especially in the New England and Middle Atlantic regions, all forest trees have been removed within 30 to 40 ft of Interstate highways, primarily for safety reasons. Because the major impact of salt is confined to within 60 ft of the highway, damage to forest trees is considerably less on highways with these large setbacks. Even under these circumstances, small trees or shrubs may be planted near the roadway for erosion or glare control.

Few measures are available to estimate tree condition along salt-treated highways. Connecticut and Michigan highway officials estimated that approximately 5 percent of forest trees along primary highways appear moderately to severely damaged (Connecticut and Michigan Departments of Transportation, personal communications). The Nevada Department of Transportation estimates that about 10 percent of coniferous trees in the Lake Tahoe basin are damaged by salt (Nevada Department of Transportation 1990). To estimate mortality rates, Nevada assumed that about 1 in 10 of moderately and severely damaged trees will not recover from salt injury and will die each year during a 10-year period.

Multiplication of the Nevada mortality index by the state estimates of tree damage suggests that between 0.5 percent and 1.0 percent—or about 0.75 percent on the average—of the forest trees in this hypothetical site might die each year during the next 10 years because of salt injury (0.10×5 to 10 percent). Multiplication of 0.75 percent by the estimated number of trees per mile (1,250 to 3,500) yields an annual loss of roughly 10 to 25 trees per mile per year for this hypothetical site ($0.75/100 \times 1,250$ to 3,500 trees per mile). If these trees were removed and replaced, most highway agencies would plant small, younger, more salt-tolerant trees. According to estimates from several state highway agencies, the average cost of removing a dead or severely injured tree and planting and maintaining a young tree

is approximately \$500. Multiplication of \$500 by the estimated 10 to 25 trees per year that might die on this site yields a cost of tree removal and replacement of \$5,000 to \$12,500.

Soil

High salt concentrations in soils may result in structureless and dense soil, which reduces water infiltration and lowers soil moisture content. High levels of sodium may cause the loss of essential plant growth nutrients such as potassium, calcium, and magnesium. If this occurs in excess, soil fertility will diminish, preventing the growth of desired vegetation or leading to soil erosion. Though salt concentrations can be elevated as far as 40 ft from the roadway, the literature suggests that it is unrealistic to assume an adverse effect on the entire band. Instead, damage is likely to be sporadic, and most damage is likely to be confined to 15 ft of the pavement edge.

In extreme cases, in which soil structure is severely altered and deficiencies in essential nutrients are discovered, soil reclamation is an option. The primary objective of soil reclamation is to improve soil infiltration and moisture retention. This can be accomplished by periodically treating the soil with gypsum if the soil is alkaline or with lime if the soil is acidic (Jacobs and Scofield 1980; Maryland Department of Transportation 1987; U.S. Soil Conservation service, personal communication). The calcium in these two products improves soil structure by removing the sodium and is also a nutrient for plant growth. Gypsum is normally applied at a rate of 10 tons per acre and costs about \$40 per ton, resulting in an application cost of \$400 per acre (Maryland Department of Transportation 1987; U.S. Soil Conservation Service, personal communication). In applying gypsum, tilling and other soil preparation is necessary, which costs approximately \$250 per acre (Maryland Department of Transportation 1987). The total remediation cost is therefore about \$650 per acre.

A 1-mi section of highway in which a 15-ft band of soil is affected on both sides of the roadway would require gypsum treatments on a total of about 4 acres of soil. At \$650 per acre, the cost of one treatment would be \$2,600 ($\650×4 acres). Treatment once every 5 to 10 years yields an average annual cost of about \$250 to \$500 during the period ($\$2,600/5$ to 10 years).

Site 2

Site 2 consists of deciduous, coniferous, or mixed forest trees adjacent to a 1-mi section of a two-lane rural (or secondary) highway with open drainage. A flat topography with no significant potential for roadside erosion is assumed. As a result, environmental damage is confined primarily to forest trees and, to a lesser degree, soils. Annual salt loadings on the highway are less than 10 tons/lane-mi, as is common on more lightly traveled roads.

Forest Trees

The tree-clear zone on the side of secondary roads is typically only 10 to 15 ft; however, because traffic volumes and speeds tend to be much lower on these roads than on primary highways, airborne salt spray and mist are less of a problem. Moreover, salt application amounts are usually lower on secondary roads, and plows rarely deposit salt-laden snow far from the roadway. As a result, tree damage is likely to be less severe on this secondary road than on the primary highway at Site 1. Almost all of the state highway agencies contacted for this study in the New England, Middle Atlantic, and Great Lakes regions indicated that tree damage on rural and secondary roads is low.

The only state that could roughly quantify this damage was Maine. About 80 percent of coniferous trees along primary highways in Maine experience some minor and temporary browning in late winter (for numerous reasons, including road salt), but fewer than 10 percent of trees on secondary roads exhibit similar effects (Maine Department of Transportation, personal communication). Multiplication of 0.125 (that is, 10/80) by the annual number of tree deaths along the primary highway at Site 1 (10 to 25 tree deaths per mile) yields a loss on the secondary road of 1 to 3 trees per year. At \$500 per tree, the cost of tree removal and replacement for this site is \$500 to \$1,500 per mile ($\$500 \times 1$ to 3 trees).

Soil

The approach used for estimating the cost to mitigate road salt effects on soil is the same as for Site 1. The major difference is that lower

vehicle speeds, traffic levels, and salt loadings result in even less salt being deposited on the roadside, reducing the frequency of gypsum treatments and other mitigation measures. Treatment once every 10 years yields an average annual cost of \$250 (see discussion of Site 1).

Site 3

Site 3 consists of forested corridor adjacent to a 1-mi section of primary highway. A drainage ditch diverts highway runoff into a stream, which flows into a small lake several miles downstream. Unlike Sites 1 and 2, a downslope from the highway to the stream is assumed. Consequently, highway runoff flows freely down-gradient, causing erosion of roadside soil.

Forest Trees

Approximately 10 to 25 trees per mile are lost due to salt injury, costing about \$5,000 to \$12,500 per year to remove and replace (see discussion of Site 1). However, this effect may be partially mitigated by the diversion of some highway runoff by the drainage ditch.

Stream Water Quality

The stream runs parallel to the highway at this site, resulting in a large portion of the water flow coming from areas in the watershed where road salt is used. Consequently, where the stream crosses the highway (Site 3 in Figure 4-2), sodium and chloride concentrations may be elevated during a thaw, as salt loadings from upstream and salty water from the drainage ditch combine. Reports in the literature indicate that chloride levels can be many times higher than usual in such circumstances, sometimes resulting in levels exceeding 500 mg/L. (In streams that receive a significant flow from unsalted areas, dilution will be greater, and chloride levels will be significantly lower.)

To protect aquatic life, Environmental Protection Agency standards (National Ambient Water Quality Criteria) for chloride concentrations in fresh water are 860 and 230 mg/L for exposure periods of 1 and 96 hr, respectively. The literature indicates that such high levels are rare. In extreme cases, as reported in the Irondequoit Bay basin in New York, chloride concentrations that reach these critical levels (which are several hundred times above normal) may harm

aquatic life, and, therefore, reduction in salt use or changes in highway drainage may be necessary for stream recovery (Bubeck et al. 1971; Diment et al. 1973).

More commonly, however, chloride levels in the stream increase by a factor of 2 to 10 times above normal, and the stream experiences a nontoxic increase in salt that fluctuates during the year. In this case, the salt loading may result in slight changes in the species of biota present in the stream rather than widespread damage to the system. Unlike the obvious browning of leaves in roadside vegetation, changes in water biota are likely to be subtle and difficult to observe. For instance, they are unlikely to result in noticeable declines in game fish population.

Lake Water Quality

The impacts of road salt on lakes are not as well understood as those on roadside vegetation. Salt loadings large enough to reduce circulation and aeration in small lakes have been documented (e.g., Hawkins and Judd 1972), but this degree of damage is exceptional. In such cases, artificial circulation using compressed air is a mitigation option. More commonly, the lake shows increases in chloride concentrations close to the point source. Even if chloride concentrations rise 20 to 50 mg/L above background, significant ecological damage or organism mortality will probably not be observed (Lillie and Mason 1983).

Roadside Erosion

It is assumed that erosion of soil occurs along the sloped roadside at this site. Salt damage to vegetation is assumed to contribute to the process, both by allowing rain to fall directly on the soil (because of a loss of vegetation cover) and by damaging the root structure holding the soil in place. Erosion is caused by many interrelated factors, and, therefore, the cost of control is always site specific. Hence, it is not possible to project a cost for this impact.

Site 4

Site 4 consists of shrubs and grass adjacent to a 1-mi section of primary highway with forest trees in the background. Forest trees do not begin until a distance of 40 to 60 ft from the highway. A flat

topography is assumed, resulting in no significant potential for erosion damage. Damage to soils, if any, is covered in the discussion of Site 1.

Shrubs and Grasses

The response of shrubs to road salt varies by species. However, many highway agencies contacted for this study report that, in general, most roadside shrubs are hardy and unaffected by salt. This is probably because salt-tolerant shrubs have been planted or natural salt-resistant species have become established over time (the time for maturity of a shrub is significantly less than that of a tree). Highway agencies report that shrubs are more often damaged by snowplows and snow accumulation due to plowing or blowing.

Few data are available to estimate the cost of shrub damage from road salt. If shrub mortality levels are one-quarter to one-half those of trees, which is plausible given their greater salt tolerance, 3 to 12 shrubs might need to be removed and replaced each year (0.25 to 0.50×10 to 25 trees). If an average removal and replacement cost of \$75 dollars per shrub is assumed on the basis of various state highway agency estimates, the total annual cost is \$225 to \$900 ($\$75 \times 3$ to 12 shrubs).

Grasses also exhibit varying degrees of salt tolerance, although they tend to be more tolerant of salt than are shrubs. Some grass damage may occur within a few feet of the pavement, and reseeding with a salt-tolerant species may be required. The approximate cost of reseeding (and fertilizing) turf is \$250 to \$500 per acre (Goldman et al. 1986). If 4 acres (see Site 1 discussion on soils for acreage estimate) must be reseeded every 5 to 10 years, the average annual cost is \$100 to \$400 ($4 \text{ acres} \times \$250$ to $\$500/5$ to 10).

Forest Trees

Because the area of shrubs and grasses is assumed to be 40 to 60 ft deep, forest trees will be affected primarily by salt spray and mist. Findings in the literature suggest that the assumption that no more than 10 percent of tree damage (see Site 1 discussion) occurs that far from the roadway is reasonable. According to the cost estimates derived for Site 1, this damage might result in 1 to 3 tree deaths per year on both sides of the highway (0.10×10 to 25 trees), costing \$500 to \$1,500 to remove and replace (1 to $3 \times \$500$).

Site 5

Site 5 consists of a maintenance yard adjacent to a highway bordered by a residential area and forest trees and shrubs. The maintenance yard is assumed to contain uncovered salt stockpiles.

It is generally agreed that on a per-unit-area basis, salt damage to the environment is more severe near salt storage and loading facilities. Many of the studies and complaints of salt damage to the environment have stemmed from improper salt storage and handling. These problems can usually be overcome by improving maintenance yard housekeeping and upgrading storage facilities, although the remediation of existing environmental damage may be necessary.

Improvement of salt storage can be accomplished in several ways. Outdoor stockpiles can be covered with a tarpaulin and placed on pads made of asphalt or other impermeable materials. Preferably, stockpiles can be stored indoors in specially built shelters, such as wooden sheds or concrete domes. Conveyor belts and special loading equipment can be used to reduce salt spillage during handling, and the loading area apron can be constructed of impermeable material that is swept clean of salt spillage on a frequent and timely basis after storms.

The cost of these improvements depends on the measures taken. The cost of installing impermeable flooring and controlling drainage may be a few thousand dollars for small outdoor stockpiles, whereas the cost of a concrete dome with specialized loading equipment for larger storage sites can exceed \$250,000.

Site 6

Site 6 consists of an orchard adjacent to a 0.25-mi section of primary highway. A flat topography with no significant potential for erosion damage is assumed.

The impact of road salt on fruit trees varies by location. The effect is similar to that of forest trees. However, the literature indicates that fruit trees may be less tolerant of salt than are common forest trees. Table 4-3 presents costs of road salt damage to orchards in Ontario, Canada, as estimated by the Ontario Ministry of Transportation (Bacchus 1987). The data are based on claims of orchard owners. It is assumed that the effects extend to orchard trees within 100 ft of either side of the roadway and that damage results in 30 to 60 percent losses in crop yield from affected trees. The loss ranges from \$475 to \$1,400 per acre, depending on the type of fruit.

TABLE 4-3 ROAD SALT DAMAGE TO FRUIT CROPS FOR SITE 6 (Bacchus 1987)

Type of Crop	Full Value of Crop ^a (\$/acre/year)	Percent of Crop Damaged	Value of Loss (\$/acre/year)
Apple	1,590	30	475
Peach	2,300	60	1,380
Mixed (apple and peach)	1,645	45	740
Other (grapes, plums, and pears)	1,445	45	650

^aConverted from 1985 Canadian dollars to 1990 U.S. dollars using an exchange rate of 0.86 and adjusted for inflation.

For this site, the affected 200-ft corridor contains 6 acres of orchard trees. The value of the loss in fruit is approximately \$2,800 to \$8,400.

SUMMARY

During the past 30 years, hundreds of articles and reports have been written documenting the impacts of road salt on the environment. The literature indicates that these impacts can be significant but depend on factors unique to each site, such as the timing and quantity of salt applied, local drainage features, weather conditions, soil type, topography, watershed size, vegetation cover and species composition, and distance from the roadway. In addition, salt impacts and other environmental perturbations, such as vehicle exhaust emissions, drought, and plant diseases and pests, are likely to interact. Hence, findings from each study must be reviewed in the light of the prevailing conditions at the particular site. The only generalization that can be made on the basis of the literature is that road salt impacts tend to diminish rapidly with distance from the roadway.

Findings from previous studies, as well as the general concerns expressed by the public and state highway agencies in various regions of the country, suggest that a plausible national ranking of these impacts, in order of overall severity, might be as follows:

<i>Rank</i>	<i>Impact</i>
1	Injury to roadside vegetation, especially trees
2	Damage to soil structure
3	Impact on surface water quality

Damage to roadside trees is a well-publicized concern in several

regions of the country, especially in forests and parklands adjacent to highways. Trees and other roadside vegetation can be injured by salt through changes in soil chemistry and from salt splash and spray on foliage and branches. The symptoms of salt injury are similar to those of drought: inhibited growth, browning and falling leaves and needles, and sometimes dying limbs and premature plant death. Under extreme conditions, roadside vegetation can be exposed to salt as far as 500 ft from the roadway, although the impact is seldom significant beyond 100 ft. Tree damage is likely to be greatest along high-traffic highways with heavy salt use and steep, downsloping roadsides. Highway agencies in states where public concern about tree damage is greatest report that 5 to 10 percent of the roadside trees in forests located along heavily traveled highways exhibit signs of salt-related decline. Roadside shrubs, grasses, and wetland vegetation are generally more salt tolerant than trees; hence, most states report relatively minor damage.

Other side effects of road salt on soil and surface water are far more site specific. Salt's impact on soils is usually confined to 15 ft from the roadway, although greater distances have been reported. Long-term salt accumulation in soil increases soil density and diminishes permeability and fertility, which may adversely affect moisture retention and soil structure characteristics that are important for plant growth and erosion control. The accumulation of salt in soils depends on many factors, including soil type, precipitation, and topography. Whether salt has a cumulative effect depends on these site-specific conditions.

Road salt's effects on surface water are confined mainly to small streams running adjacent to salt-treated highways. Although small receiving lakes and ponds can be affected, few such incidents have been reported. Salt loadings in larger rivers and lakes are usually diluted because of the high water volume. In extreme cases, high and persistent concentrations of chloride (more than 500 mg/L) in small streams may harm fish and other aquatic life. Because of the complexity of stream environments and their site-specific nature, it is difficult to characterize and quantify these potential adverse effects in the aggregate.

Consolidation of the various site-specific environmental effects of road salt into a national estimate of environmental damage or cost is not possible. Such monetary evaluations have been attempted in previous studies (e.g., Murray and Ernst 1976) to shed light on the potential magnitude of environmental damage.¹ Whereas these previous estimates have led to further study of salt's environmental impact, they

were not intended, nor can they be accurate enough, to compare the overall cost of salt with that of other deicing chemicals.

Meaningful estimates of the cost of environmental damage can be accomplished only for individual sites, whereby local circumstances can be evaluated in depth. Even when damage can be quantified for a specific site (e.g., number of trees injured), monetary values can be difficult to assign and highly subjective. Estimates of mitigation costs—such as the cost of removing and replacing an injured tree—provide some cost perspective, but they may be inaccurate or incomplete because they do not reflect the value to society of the injured tree or other indirect costs, such as diminished aesthetics and secondary effects on roadside ecosystems.

NOTE

1. For instance, Murray and Ernst (1976) estimated that the national cost of road salt damage to trees was about \$50 million, or about an order of magnitude smaller than infrastructure costs.

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ABBREVIATIONS

FHWA	Federal Highway Administration
HRB	Highway Research Board
NCHRP	National Cooperative Highway Research Program
TRB	Transportation Research Board
USDA	U.S. Department of Agriculture

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5

Road Salt Impacts on Drinking Water



Many studies during the past 30 years have linked increased salt concentrations in drinking water with highway salting operations. Concerns about road salt as a potential contaminant in drinking water date back to the 1950s, when it was discovered that salt was contaminating

drinking water supplies because of improper storage and, in some cases, highway runoff. One objection to salt in drinking water is its taste; a more serious concern is its impact on health. In recent years, considerable attention has been focused on the effects of salt on hypertension, or high blood pressure. Recommendations by government and private health care organizations for moderate salt restriction to prevent hypertension have made people more aware of sources of salt in the diet, including drinking water. Accordingly, salt's relevance to health, road salt's impact on drinking water, and measures being taken to mitigate the contamination of drinking water by road salt are reviewed in this chapter.

RELEVANCE OF SALT TO HEALTH

Salt is relevant to health primarily because it is a principal source of sodium in the diet. Salt is about 40 percent sodium and 60 percent chloride by weight. The quantity of dietary sodium is often expressed in milligrams per day. For healthy adults, the recommended minimum safe intake of sodium is 500 mg/day (NRC 1989a, 253). Sodium

is necessary for the body and cells to regulate fluids and for the transmission of electrical impulses in the nervous system and muscles (NRC 1989b, 413).

Though it is a dietary essential, sodium has been negatively associated with health primarily because of concerns related to hypertension. Hypertension is a major risk factor for cardiovascular disease and death in the United States (NRC 1989b, 414). Definitions of hypertension vary, but it is believed that between 12 and 30 percent of the U.S. population have borderline to pronounced hypertension (NRC 1989b, 550). No single factor is thought to cause hypertension; it is widely believed that several factors have an influence, including age, weight, lifestyle, family history, race, gender, and diet (NRC 1989b, 550). For most individuals with high blood pressure, the exact causes are unknown (DHHS 1988, 144).

The hypothesis that excess sodium causes or contributes to high blood pressure has dominated nutritional and dietary research in hypertension. At present, most medical researchers who have examined the evidence agree that moderate sodium restriction will reduce the prevalence of hypertension in this country by benefiting a portion of the population with the disorder and reducing the number of new cases (DHHS 1988, 152–153). The Food and Nutrition Board of the National Academy of Sciences and several governmental and private health care organizations (including the Surgeon General and the American Heart Association) recommend that Americans reduce their sodium intake by eating fewer sodium-rich foods and limiting the use of salt in cooking and at the table (NRC 1989b, 16).

Sources of Sodium in the Diet

The average daily sodium intake of adults is estimated to be 4000 to 6000 mg/day (DHHS 1988, 150). Intake of sodium is influenced almost entirely by the presence of salt in food. Salt is found naturally in varying concentrations in both vegetables and meats and is used as an additive in many foods for flavoring and preservation. Other sodium salts, such as sodium bicarbonate and monosodium glutamate, are sometimes added to foods.

The contribution of major food groups to daily sodium intake is shown in Table 5-1. According to this survey by the Food and Drug Administration (FDA), food accounts for 98 to 99 percent of daily sodium intake, and all beverages, including drinking water, account for the remaining 1 to 2 percent.

TABLE 5-1 PERCENTAGE CONTRIBUTION OF MAJOR FOOD GROUPS TO DAILY INTAKE OF SODIUM (Pennington and Young 1991)^a

Food Group	Age and Sex Group (%)					
	6-11 months		2 years		14-16 years	
					F	M
					30-35 years	
					F	M
					60-65 years	
					F	M
Vegetables	6	7	8	8	10	9
Fruits	1	0	0	0	0	0
Grain products	21	26	25	25	24	26
Nuts	0	1	1	1	1	1
Dairy products	35	16	12	12	12	10
Eggs	4	3	1	2	2	2
Animal flesh	8	16	17	17	19	23
Mixed dishes	17	18	20	20	18	17
Desserts	5	7	9	9	7	7
Sweeteners	0	1	2	2	1	2
Fats and sauces	3	4	5	4	6	5
Beverages, including drinking water	1	1	2	1	2	2

NOTE: F = female, M = male. Columns may not sum to 100 because of rounding.

^aDietary intakes of sodium by specific age and sex group in the United States as determined by the Food and Drug Administration's Total Diet Study from 1982 to 1989. The foods selected for the Total Diet Study represent the core foods of the U.S. food supply as determined by the U.S. Department of Agriculture. Discretionary salt that is added to food during cooking and at the table was not included in the study. All regions of the country are represented in the study.

daily. AHA has no position on sodium concentrations in drinking water for the general public.

The federal Safe Drinking Water Act requires EPA to periodically update drinking water quality criteria. The criteria, which generally reflect the latest scientific knowledge, are announced through Federal Register notices for explanation of rationale and for public comment. EPA does not regulate sodium because of the normally minor contribution of drinking water to daily sodium intake (*Federal Register* 1985, 46,890; *Federal Register* 1988, 1,894). As a general guidance level, EPA recommends that sodium concentrations in drinking water not exceed 20 mg/L for the higher-risk population (i.e., persons on low-sodium diets), on the basis of dietary recommendations by AHA. Currently, EPA requires that all public water systems monitor sodium levels and report levels greater than 20 mg/L to local health authorities so that physicians treating people on sodium-restricted diets can advise patients accordingly (40 CFR 141.4).

For comparison, regulatory norms in the European Economic Community allow sodium concentrations in drinking water of up to 125 mg/L (Van der Veen and Graveland 1988, 52). If contributed by sodium chloride, this level is equivalent to roughly 250 mg/L chloride, at which level dissolved salt can usually be tasted.

ROAD SALT CONCENTRATIONS IN DRINKING WATER

Road salt can enter water supplies by percolation through soil into groundwater or runoff and drainage directly into reservoirs. Upon entering fast-flowing streams and larger rivers and lakes, salt runoff usually has little effect, because concentrations are quickly diluted (Hanes et al. 1970, 19). Road salt infiltration is more common for groundwater-based supplies, such as wells, springs, and reservoirs that are recharged primarily by groundwater.

Road salt can reach groundwater in several ways. For example, many highways, especially in rural areas, use "open" drainage systems, whereby highway runoff is not collected and diverted by gutters and catch basins but instead flows off the pavement into unlined ditches and roadside soil (Pollock 1990, 2). In addition, road salt applied during snowstorms often mixes with snow that is plowed completely off the roadway and paved shoulder. When the snowbanks melt, the meltwater, together with the dissolved salt, can migrate through the soil and move to the water table (Pollock 1990, 2). In colder regions where large snowbanks accumulate during the winter,

spring thaws can produce high concentrations of salt. For example, meltwater samples near several large snowbanks in Wisconsin contained sodium concentrations exceeding 1000 mg/L (Schraufnagel 1965).

The ability of road salt to reach groundwater depends on a number of factors, including the frequency of precipitation and the texture and drainage characteristics of roadside soil. Only a portion of the sodium ever reaches the groundwater. Moreover, whether the saltier groundwater beneath the highway will eventually migrate into nearby wells depends on several factors, including the depth of the well and its distance from the highway, the permeability of the aquifer material, and the direction and rate of groundwater flow (Pollock 1990, 5). Wells most likely to be affected are those within 100 ft down-gradient of the roadway in the direction of groundwater movement. In locations where groundwater moves slowly (e.g., a few feet per year), road salt concentrations may have originated, at least in part, from highway runoff generated several years earlier (Pollock 1990, 5).

Perhaps the state most actively monitoring the effects of road salt on drinking water is Massachusetts, which has done so regularly for the past 25 years. Sodium concentrations of 10 mg/L are natural throughout much of the state (Pollock 1988). The number of public water systems reporting sodium levels twice the natural level jumped from 69 in 1970 to 95 by 1973, the period during which road salt use peaked (Massachusetts Department of Public Health 1973; Murray and Ernst 1976, 15). After several years of investigating and resolving salt contamination complaints, however, the number has dropped to 63 (Pollock 1990, 2). Of the 363 public water systems in the state, 45 are within the range 20 to 40 mg/L and 18 are greater. The single highest concentration is 95 mg/L (Pollock 1990, 2). The highest sodium concentrations in Massachusetts are currently in the more urban, eastern half of the state, where road salt use is heaviest.

In addition to monitoring public water systems for sodium, Massachusetts investigates complaints of salt contamination in private water supplies. Since 1973, for example, the state has regularly monitored seven residential wells located along a section of highway where salt contamination complaints are common. The average median sodium concentration in these wells was 79 mg/L between 1973 and 1983, before any remedial action (Pollock 1990). Since 1983, in response to complaints by residents, the state has instituted a reduced-salting program along this section of highway. Straight salt was replaced by sand and a mixture of salt and calcium chloride. The state believes that this program has succeeded in both identifying and diminishing the effect of salt runoff on roadside wells (Pollock 1990). Four years

after the program began, average sodium concentrations in the wells dropped by more than 50 percent, from 79 to 36 mg/L (Pollock 1990).

The experience in Massachusetts indicates that highway runoff can elevate sodium levels in water supplies. Because so few states routinely monitor the effect of road salt on water supplies, however, it is difficult to characterize the impact of salt runoff nationwide. In the survey of state highway agencies conducted for this study, seven other states reported that they periodically investigate and monitor runoff in water supplies. Of these states, the most active are New Hampshire, Connecticut, and New York. Altogether, 16 states reported receiving complaints related to road salt contamination of drinking water during the past 10 years. The number ranged from one or two per year in Maryland, West Virginia, and Ohio to several dozen per year in the New England states and New York. As might be expected, most states that reported complaints are located in the Northeast and Great Lakes regions, where population densities are highest and road salt use is heaviest.

MITIGATION MEASURES

The first complaints of road salt contamination of water supplies were during the 1950s and stemmed mainly from improper salt storage. At that time, salt piles were often left uncovered and lacked drainage and flooring adequate to prevent salt from migrating into surrounding soils and groundwater.

During the past 20 years, many highway agencies have made efforts to improve storage. They have constructed facilities with contained drainage and leakproof covering and placed impervious pads under stockpiles and salt-handling areas (TRB 1974, 6–7). In Massachusetts, for example, road salt used by state agencies is stored in covered buildings with bituminous concrete flooring; in addition, highway crews pay special attention to minimizing salt spillage during loading and immediately clean spills in salt-sensitive areas (Pollock 1988, 11). Results from the survey of highway agencies for this study indicate that most states that have taken such remedial action have done so primarily because of complaints related to poor storage. Michigan, Ohio, Indiana, and New York, for example, have done so following litigation. In New England, Vermont and Maine spend about \$35,000 and \$75,000 per year, respectively, to upgrade storage facilities and replace nearby contaminated wells when necessary. At least one state, Illinois, has enacted legislation requiring all storage sites to be located at least 200 ft from water supplies.

Though it appears that most egregious salt storage problems are now being corrected, during the past 20 years concerns about the potential for salt contamination of water from highway runoff have increased (Murray and Ernst 1976, 14). Highway surface runoff seldom results in sodium concentrations as high as those associated with poor salt storage, but it can be a difficult problem to redress because of the widespread use of road salt and the potential for numerous water supplies (e.g., public and private wells) to be affected. Measures taken to remedy road salt runoff problems vary widely by state and local jurisdiction, depending on the extent of the problem and the level of awareness and concern by the community and government agencies. Typical remediation measures include highway drainage changes, reduction of salt use near water supplies, delivery of bottled water, and connection of well users to public water systems.

In the survey of state highway agencies, nine states reported taking action to mitigate salt runoff into water supplies during the past 10 years. For the most part, these states are in the Northeast and Great Lakes regions. For instance, New Hampshire has replaced private wells contaminated by road salt for more than 30 years. During the 1960s and 1970s, when its well-replacement program was at its peak, about 40 wells per year were replaced at a typical cost of \$2,000 per well (Murray and Ernst 1976, 59–60). Today, the state spends about \$200,000 per year to divert highway runoff from sensitive areas (through drainage improvements) and replace wells when necessary. The program operates on a complaint basis only, when it is determined that road salt is responsible for chloride concentrations in well water exceeding 250 mg/L, which indicates sodium concentrations of about 125 mg/L.

Again, perhaps the most active mitigation program is that of Massachusetts. Between 1982 and 1988 the state spent nearly \$1.5 million to investigate and remediate the 119 complaints it received about salt contamination of private wells (Pollock 1988, 1). Among the actions taken were

- Well replacement,
- Connection to public water supplies,
- Water treatment (temporary use of reverse-osmosis filters),
- Improvements in highway drainage, and
- Use of salt substitutes.

Table 5-2 shows expenditures in Massachusetts between 1982 and 1988 by mitigation measure. By far the most common measure was connection of well owners to public water systems. In 1984 and 1985,

TABLE 5-2 DISPOSITION OF ROAD SALT CONTAMINATION COMPLAINTS BY PRIVATE WELL OWNERS IN MASSACHUSETTS, 1982-1988 (Pollock 1988)

Year	Well Replacement	Public Supply Connection	Water Treatment	Drainage Change	Salt Substitute	Other	Annual Expenditure for Fiscal Year (\$)
1982			7				55,150
1983	2						67,548
1984	1	32		1			442,260
1985		2					27,085
1986	1	1				3	416,347
1987	10	12				2	118,672
1988 ^a	<u>9</u>	<u>14</u>	<u>-</u>	<u>1</u>	<u>20</u>	<u>1</u>	<u>349,750</u>
Total	23	61	7	2	20	6	1,476,812

^aHalf-year total.

for example, 34 wells with sodium concentrations exceeding 20 mg/L were connected to public water systems at a cost of \$430,000, or about \$13,000 per complaint. Well replacement (whereby wells are drilled deeper and carefully sealed) is the next most common method of remediation, accounting for the resolution of 23 complaints, at a cost of \$5,000 to \$30,000 per well. Remediation expenditures averaged about \$12,500 per complaint for the 119 complaints resolved.

In addition to remediating the effects of salt contamination on private water supplies, Massachusetts has acted to reduce sodium levels in some public water systems. Remediation measures include reduced salting in the vicinity of water supplies and, in a few cases, construction of special drainage systems to divert highway runoff. As mentioned previously, the reduced-salting program in Massachusetts generally involves greater use of sand and a deicer "pre-mix" of 80 percent sodium chloride and 20 percent calcium chloride. The reduced-salting program was initiated when a reservoir near several state highways was found to have sodium concentrations fluctuating from 30 to 60 mg/L. In another instance, a special highway drainage system was constructed that collects meltwater from plowed snowbanks on the median and highway shoulders (Pollock 1984). The system, constructed on a 2-mi section of freeway near Cape Cod, cost about \$2.5 million/mi more to build than a conventional system (Pollock 1988).

Other mitigation (and in some cases prevention) measures adopted by state highway agencies include a special \$2 million drainage system in Pennsylvania-constructed on an Interstate highway passing several large water supplies-and the installation of test wells in Ohio and New Jersey to monitor sodium concentrations in groundwater near salt-treated highways.

COST

Two cost items related to road salt contamination of drinking water are mitigation expenses and potential public health effects.

Mitigation Costs

Only nine state highway agencies reported annual spending on prevention and remediation of salt-contaminated water supplies. How-

ever, the nine states apply about one-half of all salt used by states, and their reports are useful reference points for estimating nationwide spending on prevention and remediation. All nine states—Illinois, Indiana, Maine, Massachusetts, Michigan, New Hampshire, New York, Pennsylvania, and Vermont—are located in the northeastern and central United States, where concerns about salt contamination of drinking water are greatest.

Mitigation spending by these states totaled about \$1.8 million in 1989, or, on the average, about \$1 per ton of salt applied (Table 5-3). Accordingly, a rough estimate of national expenditures on mitigation measures is that about \$10 million is spent each year for the 10 million tons of salt applied annually by state and local highway agencies.

Public Health Costs

Ideally, an estimate of the total cost of salt contamination of drinking water would include not only those resources spent on mitigation but also any adverse effects on public health when mitigation is inadequate. Such a thorough determination of costs, however, is complicated by the lack of evidence linking salt in drinking water

TABLE 5-3 STATE SPENDING ON PREVENTION AND REMEDIATION OF DRINKING WATER CONTAMINATION BY ROAD SALT, 1989

State	State Expenditures ^a (\$)	Amount of Salt Spread Annually by State ^b (tons)
Illinois	200,000	275,000
Indiana	175,000	240,000
Maine	75,000	60,000
Massachusetts	500,000	225,000
Michigan	200,000	350,000
New Hampshire	195,000	125,000
New York	175,000	450,000
Pennsylvania	200,000	425,000
Vermont	35,000	100,000
Total	1,755,000	2,250,000

^aFrom survey of state highway departments.

^bFrom survey of state highway departments and Salt Institute data.

with a health risk to the general public. As a result, no attempt was made in this study to estimate public health risks and costs.

SUMMARY

Road salt can enter drinking water supplies by migrating through soil into groundwater or by runoff and drainage directly into surface water. In general, only wells or reservoirs near salt-treated highways or salt storage facilities are susceptible to salt infiltration. Susceptibility depends on many factors, such as salting intensity, soil type, climate, topography, and water volume and dilution. Sources of salt in drinking water other than road salt include natural brines and salt deposits, industrial and agricultural chemicals, and water treatment and softening processes.

During the past 30 years, communities in several states, primarily in the Northeast, have reported higher sodium and chloride concentrations in private wells and public water supplies that have been linked to road salt. Many of these problems have resulted from improper salt storage. Most of the more egregious salt storage problems are being corrected. Some communities continue to report higher-than-usual salt concentrations in water supplies due to highway runoff, although such concentrations are seldom as high as those associated with improper salt storage.

The discovery of higher salt concentrations in drinking water due to road salt has raised concerns about possible adverse effects on public health. Salt is a source of sodium in the diet. Excess dietary sodium has been negatively associated with health primarily because of concerns related to hypertension, or high blood pressure. Typically, drinking water and all other beverages combined (which tend to have much higher concentrations of sodium than drinking water) account for less than 5 percent of daily sodium intake. Because of the normally minor contribution of drinking water to sodium intake, no federal standards have been established for salt (i.e., sodium or chloride) concentrations in water supplies.

Efforts to mitigate salt impacts on drinking water vary from state to state and by community. Common measures include modification of highway drainage, relocation of private wells, upgrading of salt storage facilities, and reduced salting activity in the vicinity of public water supplies. Nationally, about \$10 million is spent on mitigation each year by state and local governments, mostly in the Northeast and Midwest. Potential costs due to road salt in drinking water other than government spending on mitigation are largely unknown, prin-

cipally because of the uncertain effects of salt on health. As a result, no attempt was made in this study to estimate other costs of salting, if any, that might be related to public health.

REFERENCES

ABBREVIATIONS

AHA	American Heart Association
DHHS	Department of Health and Human Services
EPA	Environmental Protection Agency
HRB	Highway Research Board
NRC	National Research Council
TRB	Transportation Research Board

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6

Calcium Magnesium Acetate



What is known about calcium magnesium acetate (CMA) is reviewed in this chapter. The discussion is organized into five sections covering its (a) discovery and development, (b) field experience, (c) environmental and health evaluations, (d) compatibility with automotive

and highway materials, and (e) production technologies and market price.

DISCOVERY AND DEVELOPMENT

During the 1970s the Federal Highway Administration (FHWA) initiated a research program aimed at reducing the overall cost of highway deicing. An important part of this program was an investigation of deicing chemicals as possible replacements for salt (sodium chloride, or NaCl) (Dunn and Schenk 1980a). Most chemicals considered were eliminated quickly in preliminary evaluations because they were prohibitively expensive, not available in sufficient quantities, had unsuitable physical or chemical properties (e.g., were gaseous or not water soluble), or were corrosive, flammable, toxic, or harmful to the environment. On the basis of literature surveys and limited laboratory studies, the field was narrowed to two candidate chemicals, methanol and CMA (Dunn and Schenk 1980b, 13).

Methanol, a liquid sometimes used as an antifreeze, is particularly effective at very low temperatures. CMA, a solid, has a deicing range

closer to that of salt. Whereas both chemicals were deemed suitable from the standpoint of a number of deicing criteria, CMA was selected for continued development because of its greater environmental acceptability and handling and spreading characteristics that more closely resembled those of salt.¹ Preliminary laboratory tests and literature reviews indicated that it is harmless to plants and animals, noncorrosive to metals, and nondestructive to concrete and other highway materials. Because its main ingredient, dolomitic lime, is abundant throughout much of the country, it was anticipated that economical methods of production could be developed quickly.

Soon after CMA's discovery, FHWA, with financial support from 24 state highway agencies, began to investigate its deicing properties and use characteristics in the field. Initial field tests were conducted by Michigan and Washington State during the winters of 1983 and 1984 (Defoe 1984; Ernst 1984). Each state was provided 100 tons of an early test product to use on freeway sections in comparison with salt. The main objective of these tests was to determine CMA's deicing effect. Other areas of investigation were its storage, handling, and spreading characteristics. Test results were generally promising, although the following drawbacks were reported:

- Because of its low density and small particle size, the test material was dusty during handling and storage and tended to blow off the roadway after spreading. When exposed to moisture, it frequently caked and clogged spreading equipment.
- The test material was often less effective than salt in colder conditions and slower acting and less successful in penetrating heavy snowpack and ice.
- Typically, twice as much CMA had to be used as salt (by weight).

On the basis of these findings, both states recommended that CMA's physical form be altered to either a liquid or larger particles to improve its spreading and handling qualities and its ability to penetrate packed snow and ice (Defoe 1984; Ernst 1984).

On completion of the field trials, efforts to improve CMA's performance were already under way. In 1983, FHWA sponsored additional research aimed at determining the optimum calcium/magnesium (Ca/Mg) ratio (Schenk 1985). The test product used in Michigan and Washington State had a Ca/Mg ratio of 1 to 1. However, findings from this subsequent research indicated that the higher solubility and lower freezing point of magnesium acetate favored a Ca/Mg ratio with a higher proportion of magnesium, on the order of 1 to 2.3 (Schenk 1985).

The primary producers of CMA at the time—Chevron Chemical Company, Verdugt, Inc. (Netherlands), and Gancy Chemical Company—changed their CMA products to reflect this formulation. In addition, the largest producer, Chevron, developed a harder, pelletized version that was expected to be less dusty, flow more freely from spreading equipment, and penetrate ice faster than the lighter, powdery material used in Michigan and Washington State (Figure 6-1).

FIELD EXPERIENCE

Since 1985, at least six jurisdictions—California, Massachusetts, Wisconsin, the city of Ottawa, and the Canadian provinces of Alberta and Ontario—have reported on their field evaluations of CMA. Summarized in the following sections are results from these evaluations and responses from other CMA users who were interviewed for this study. Findings concerning CMA's deicing performance are reviewed first, followed by its storage, handling, and spreading characteristics.

Deicing Performance

The theoretical amount of CMA relative to salt needed for comparable ice melting is 1.7 to 1 by weight.² In practice, however, ice-

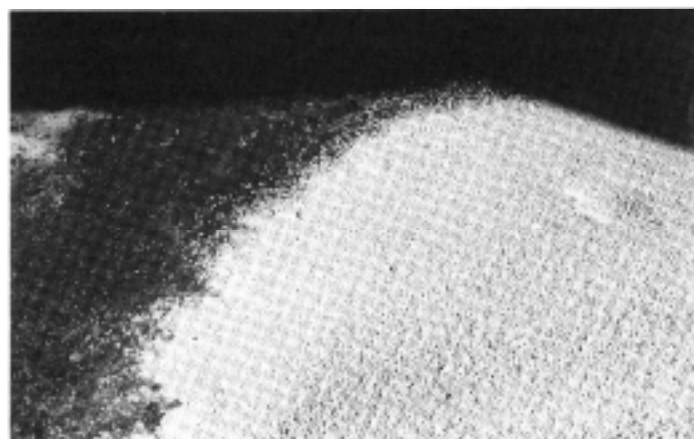


FIGURE 6-1 Pelletized CMA in storage.

melting capacity is not the only characteristic important to deicing. As the following results from field tests indicate, chemical deicing also involves ice prevention, penetration, disbonding, and interactions with traffic and weather.

Ontario

Ontario compared CMA with salt by spreading each deicer on different sections of the same freeway segment (Manning and Crowder 1989). During the two winters tested (1986–1987 and 1987–1988), 34 storms occurred. Most were short and mild; temperatures seldom dropped below -5°C (23°F), and snowfalls were typically light. CMA and salt were applied at specified rates, and the number of applications was dictated by conditions.

During the first winter, CMA/salt application rates were initially specified at 1.7 to 1 by weight; however, this rate was deemed excessive and eventually lowered to 1.5 to 1. In general, CMA was found to be effective in penetrating light snowpack and preventing the pavement-ice bond, which facilitated mechanical snow removal by traffic action and plowing. The authors noted that when applied at the outset of storms, it performed well as an anti-icer, preventing the accumulation of snowpack and ice. The CMA treatments were also found to be more effective during longer storms, and the tendency of CMA residue to adhere to the pavement was thought to have reduced treatments during subsequent storms.

Overall, CMA was found to be as fast and effective as salt in achieving bare pavement under the conditions tested. Its endurance during longer storms, residual effect from storm to storm, and performance as an anti-icer, however, were found to be advantages that helped reduce the total number of CMA applications required compared with salt. During the entire test period, 20 to 40 percent more CMA was used than salt.

Wisconsin

Field tests in Wisconsin were part of a second round of FHWA-state efforts to evaluate the deicing properties and operational characteristics of CMA (Wisconsin Department of Transportation 1987; Smith 1989). As in Ontario, the tests were conducted on freeway sections. During the two winters tested (1986–1987 and 1987–1988), 43 storms occurred, most of which were short and mild.

CMA was applied in quantities ranging from 1.2 to 1.6 times greater than those of salt. At these rates its deicing performance was comparable with that of salt. It required no additional time to achieve bare pavement, although it was slower starting than salt (by about 20 min). It was effective in preventing the pavement-ice bond but less successful than salt in melting snow and ice accumulations, requiring traffic action or plowing for mechanical removal. It was less effective than salt when applied to fluffy (dry) snow and when temperatures dropped below approximately -5°C (23°F). In contrast to results in Ontario, no endurance or residual effects were noticed during longer storms or from storm to storm. By the end of the test period, approximately 60 percent more CMA had been applied than salt.

Massachusetts

Massachusetts first tested CMA in the field as part of its reduced salt experiments during the winter of 1986–1987 (Massachusetts Department of Public Works 1987). The test site was a 4.8-mi section of two-lane suburban highway. An adjoining 4.9-mi section of salt-treated highway was monitored for comparison. CMA was used on 19 storms; with few exceptions, storm conditions were typical of southeastern Massachusetts, with high humidities, wet snowfall, and temperatures ranging from -5°C to above 0°C (23°F to above 32°F).

Throughout much of the winter, CMA was released from spreader trucks at the same rate as salt (300 lb/lane-mi). Rates were increased by approximately 20 percent during colder and drier (low-humidity) conditions. As reported in other field tests, CMA did not perform as well as salt when temperatures dropped below -5°C (23°F) and during heavy snowfall and freezing rain. Traffic action or plowing was important for snow removal when melting was inadequate. Because of recording errors and problems with study design, reliable comparisons of salt and CMA application quantities were not made.

Ottawa

During the winter of 1987–1988, the city of Ottawa sponsored field tests of CMA to determine its effectiveness on city streets (Sypher-Mueller International 1988). CMA and salt were tested on separate test routes selected from low- and high-traffic urban streets. A total of 53 storm and weather conditions were tested. Most storm temperatures exceeded -5°C (23°F).

Depending on storm conditions, CMA was applied in quantities ranging from 1 to 3 times those of salt, but typical amounts were between 1.3 and 1.8 times greater. By experimental design, the frequency of application did not vary by deicer. Unlike the experience in Ontario, no residual or endurance effect was reported. As in previous field tests, the CMA treatments were slower acting than the salt treatments and less effective in colder temperatures (below -5°C) and low traffic. Overall, roughly 60 percent more CMA (by weight) was applied than salt during the total test period.

California

California regularly used CMA on a number of mountain highways during successive winters from 1986 to 1989, primarily to reduce tree damage along scenic highways (California Department of Transportation 1989). The test sites experienced heavy snowfalls and storm temperatures ranging from mild to very cold. CMA was found to be most effective in preventing the formation of snowpack. Accordingly, attempts were made to apply it at the beginning of storms, when it could mix with initial snowfall and change the consistency to plowable meal or slush. The CMA treatments were generally slower and less effective than the salt treatments in removing heavy snowpack; the pellets penetrated slowly and often did not yield sufficient brine to flow under accumulations and break the pavement-ice bond.

Comparisons of salt use data from previous years suggested that CMA was used in quantities slightly greater than those of salt. On the basis of storm-to-storm observations, however, maintenance engineers estimated that CMA/salt use ratios were approaching 1 to 1 as familiarity with the product increased.

Alberta

Alberta tested CMA during the winters of 1987–1988 and 1988–1989 as part of its research program to reduce corrosion of bridges (Chichak and Filipiak 1989). The Peace River Bridge in northwest Alberta was selected as a test site because of its frequent corrosion problems and harsh climatic conditions [storm temperatures average -13°C (9°F)].

During initial tests, CMA was found to be less effective when temperatures dropped below approximately -5°C (23°F) and under conditions of heavy snowpack, causing maintenance crews to switch

back to salt. At temperatures above -5°C (23°F), its deicing performance was rated as satisfactory—although somewhat slower than salt—when applied in amounts 1.3 times greater.

Other Users

During the past five winters, a few highway agencies have been using CMA on a more regular, although highly selective, basis. According to estimates provided by Chevron, about 10,000 tons of CMA has been purchased since 1986 (Chevron deicing technology representative, personal communication). Current or recent users include

- California, on several mountain highways in the Sierra Nevada;
- Denver, on new concrete viaducts;
- Massachusetts, on a six-lane Interstate highway and a two-lane suburban highway (Figure 6-2);
- Michigan, on a new long-span segmental bridge (Zilwaukee Bridge);
- Nebraska, on new concrete viaducts and highway sections;
- Nevada, on mountain highways near Lake Tahoe;
- Ontario, on a two-lane rural highway; and
- West Virginia, on a four-lane, single-span bridge constructed with weathering steel (New River Gorge Bridge).³



FIGURE 6-2 Massachusetts highway treated with CMA.

Each of these users was contacted for this study and asked about CMA's performance. Most comments concerning CMA's deicing effect were similar to those from reports cited previously. In general, CMA was described as an acceptable deicer, although not quite as effective or consistent as salt. Often it was described as slower acting than salt, taking 15 to 30 min longer to start melting. Most users noted that it had to be applied early during a storm cycle; otherwise its effectiveness was significantly reduced. When applied at the outset of a storm, it was judged effective in preventing snowpack and pavement bonding. Typically, it was used in the same temperature range as salt, although it was less effective at temperatures below about -5°C (23°F). Some users reported that it did not work well in freezing rain and fluffy snow.

Several highway agencies estimated that CMA/salt ratios were starting to approach 1 to 1 as experience with the product increased. Nebraska and West Virginia found that about 30 to 50 percent more CMA than salt (by weight) was required for the first application during a storm but that application amounts could be reduced during follow-up treatments. Three highway agencies suspected that CMA provided some residual deicing effect (during secondary storms) by adhering to the pavement for several days.

Storage, Handling, and Spreading Characteristics

In its early test form, CMA proved difficult to adapt to handling and spreading practices. After initial field trials in 1983–1984, Michigan and Washington State reported that it was dusty during handling, often blew off the roadway, and adhered to spreading equipment when exposed to moisture (Defoe 1984; Ernst 1984).

Since the preliminary tests, CMA's physical form has been changed to alleviate some of these problems. Chevron developed a pelletized version designed to be more resistant to attrition, less prone to dusting and blowing, and better able to penetrate packed snow than the powdery CMA product used in earlier field trials. In field applications since 1985, CMA's storage, handling, and spreading characteristics generally have been described more favorably. Findings from evaluations and interviews with CMA users are summarized as follows:

- Ontario reported storage, handling, and spreading characteristics comparable with those of salt (Manning and Crowder 1989). CMA stockpiles were stored in an enclosed shed. Some dusting occurred during loading, but protective dust masks were not required.

However, because dusting tended to increase during prolonged storage (periods exceeding 6 weeks), well-ventilated storage facilities were recommended. Regular salt-spreading equipment was used for all treatments. Some blowing occurred during spreading, but not enough to require the covering of trucks. As in previous field trials, some inconveniences were created by wet CMA clogging and sticking to spreading equipment. Releasing CMA over a slowly rotating spinner wheel (rather than through the chute used for salt) and periodically knocking the clogged material from equipment helped minimize these difficulties.

- Wisconsin also reported few difficulties in storing, handling, and spreading CMA (Wisconsin Department of Transportation 1987; Smith 1989). The test material was stored in ½-ton sacks in an enclosed shed. Initial attempts to empty the sacks into spreader trucks proved cumbersome and time-consuming, but more efficient loading techniques were eventually discovered. Some dusting and blowing occurred, but protective dust masks were not required. Trucks were covered with tarpaulins to reduce wind scatter; otherwise, equipment was not modified. When wet, CMA occasionally clogged equipment, and CMA spray sometimes adhered to the windshields of trucks and passing cars. Overall, CMA's handling and spreading characteristics were described as close to those of salt, though somewhat less convenient for routine use.

- Massachusetts purchased CMA in bulk and stored it in stockpiles in a wooden shed (Massachusetts Department of Public Works 1987). Regular salt-spreading equipment was used for all applications, though trucks were covered to reduce blowing. In general, dusting and blowing were found to be less severe under moist conditions. Contact with moisture, however, increased caking and sticking. Overall, these problems were rated as only minor drawbacks that did not significantly affect handling and spreading.

- California normally purchased CMA in bulk and stored it in enclosed sheds (California Department of Transportation 1989). Rather than build additional storage facilities, small purchases were made frequently. Regular salt-spreading equipment was used, although spreader trucks were sometimes covered during wet and windy conditions. As in other field trials, the CMA tended to stick to and clog equipment when it became wet from tire splash and precipitation; however, its storage and handling qualities were generally described as manageable.

- Many of the CMA users interviewed for this study reported some difficulties in handling and spreading CMA, but most were characterized as minor. When wet, CMA tended to clog spreading

equipment and adhere to truck beds. Several reported that CMA spray occasionally stuck to the windshields of passing cars. All experienced dusting during loading and unloading, which sometimes required workers to use dust masks. Most stressed the importance of storing CMA indoors and covering trucks to prevent blowing and reduce exposure to moisture. One user, Ontario, resolved some of these problems by storing CMA in a watertight silo to reduce exposure to moisture and minimize handling through gravity loading.

Summary of Field Experience

Although findings are not always consistent, the experiences of CMA users provide some general insights into CMA's field performance relative to salt. Most users reported that CMA worked adequately but not quite as effectively or in quite the same manner as salt. Unlike salt, it did not produce significant surface melting and flowing brines that melt ice from top to bottom. It worked best when applied at the outset of a storm, before significant snow and ice accumulation. When applied early, it was able to mix with the falling snow and prevent the formation of snowpack and the bonding of ice to the pavement. It performed best when accompanied by plowing or traffic activity, which was important for removing loose snow and ice from the pavement. In situations characterized by light traffic and limited plowing or when ice and snowpack were allowed to accumulate, its performance was often markedly reduced. Whereas salt also worked best when accompanied by traffic and plowing, its ability to produce surface melting made traffic activity and early application less important factors.

Users also reported that CMA performed somewhat less successfully than salt at lower temperatures and in certain types of storm conditions. Although slightly slower acting, its performance was generally comparable with salt's at storm temperatures above -5°C (23°F).⁴ At these temperatures, it started to penetrate light snowpack within 15 to 30 min of salt (salt acted almost immediately). When used during colder conditions, however, its relative effectiveness diminished. For instance, at storm temperatures below -5°C (23°F), its performance was frequently judged inadequate. It was also described as less effective than salt during freezing rain and storms characterized by fluffy snow.

Most users indicated that between 20 and 70 percent more CMA than salt was required during the winter. Spreader units were typically calibrated to release about 50 percent more CMA than salt,

although CMA was sometimes applied less frequently during longer storms. Several highway agencies found that early application (i.e., at the outset of the storm, before significant snow and ice accumulation) was critical and helped improve its effectiveness and reduce the amount used. As might be expected, highway agencies with the most experience using CMA developed more successful use strategies that helped reduce application quantities over time.

The general conclusion reached by most users was that CMA's handling and spreading characteristics are comparable with those of salt. No major problems were identified. The most frequently cited drawback was its tendency to cake and stick to spreading equipment, which required operators to periodically chip or knock loose accumulations between applications and during cleanup. Generally, however, this problem was described as only a minor inconvenience. The field reports indicate that dusting and blowing were less troublesome than reported in pre-1985 field trials, though in many cases protective dust masks and truck covers were still required during handling and spreading.

CMA had to be kept dry during storage, usually in enclosed and well-ventilated shelters. Because most tests were conducted using small quantities, users could not project storage requirements for prolonged and larger-scale use. CMA is less dense than salt, requiring about 60 percent more space per ton. As a practical matter, therefore, the effect of larger-scale use on existing storage and truck capacities is likely to be an important consideration for users. Hence, on the basis of product density differences alone (not including differences in tonnage requirements), one would expect that significantly more storage and truck capacity would be required if CMA is used as a more general replacement for salt.

HEALTH AND ENVIRONMENTAL EFFECTS

During initial investigations that identified CMA as a promising replacement for salt, no potentially significant environmental or health-related impacts were uncovered (Dunn and Schenk 1980a). Literature reviews indicated that the calcium and magnesium in CMA might increase water hardness, but only if unusually large amounts entered a water system.

Since the initial work, FHWA, states, and private industry have sponsored research aimed at more thoroughly examining impacts on the environment and human health. Findings from the two most comprehensive studies, conducted by the California Department of

Transportation (Caltrans) and the National Cooperative Highway Research Program (NCHRP), are summarized in the following sections.

Caltrans Study

The purpose of this FHWA-sponsored study (Winters et al. 1985) was to examine CMA's environmental impacts before initial field tests were conducted. The study consisted of an extensive literature review and limited laboratory tests to identify potential impacts on aquatic life, terrestrial vegetation, and air and water quality. Tests consisted of aquatic bioassays on fish and plankton, irrigation and foliar spray applications to potted plants, and soil-leaching experiments. A reagent-grade mixture of calcium acetate and magnesium acetate was used in the tests.

Major findings were as follows:

- CMA was less toxic to fish (rainbow trout and fathead minnows) than NaCl. Continuously maintained CMA concentrations of 5000 mg/L were associated with slightly delayed hatching in rainbow trout.
- CMA was more deleterious to plankton (algae and water flea) than NaCl at high exposure levels. Inhibitory effects in algae occurred at CMA concentrations of 85 mg/L, and effects in water flea occurred at concentrations between 125 and 250 mg/L. Algae did not exhibit any inhibition from NaCl (at test concentrations), and the detrimental concentration for water flea was 2500 mg/L.
- CMA solution, when leached through soils, tended to exchange calcium and magnesium with other metals already present in the soils. Results indicated that CMA could extract iron, aluminum, sodium, and potassium from roadside soils.⁵
- CMA was less harmful to plants than NaCl. Of the 18 tree species tested, only one, the Russian olive, was damaged more by CMA than NaCl.
- No potential health, water, or air quality impacts were uncovered in the literature.

On the basis of these findings, the study authors concluded that at concentrations likely to be generated by highway deicing, CMA was likely to be less environmentally damaging than salt and did not appear to pose health hazards that precluded further controlled field testing. The study recommended, however, that before widespread use of CMA was considered, additional laboratory and field tests be

conducted to investigate impacts on metals in roadside soils and to track environmental effects over an extended period of time.

NCHRP Study

Following completion of the Caltrans study, researchers at the University of Washington embarked on an NCHRP-sponsored study (Horner 1988) to further assess CMA's environmental impacts and to develop interim guidelines for its safe use. As in the Caltrans study, bioassays were designed to examine effects on aquatic life, common roadside plants were irrigated and sprayed with CMA, and soils were tested to evaluate physical and chemical impacts. In addition, the study included a model predicting CMA's transport characteristics in runoff, groundwater, and soil water. The CMA product used was manufactured from acetic acid derived from corn silage.

Major findings were as follows:

- **Transport characteristics:** The transport model predicted that average highway spray and runoff concentrations of CMA would range from 10 to 100 mg/L, and extreme concentrations would not exceed 5000 mg/L. Average annual CMA loadings of 10 tons per mile were predicted.

- **Soil:** In soil at air temperatures above 10°C, a high level of CMA (acetate) decomposition was achieved within 2 weeks, whereas at 2°C, 4 weeks was required for full decomposition. CMA did not significantly affect the physical properties of soil (e.g., permeability, plasticity, and strength); however, laboratory and field tests indicated a potential for CMA to mobilize and release trace metals from soils. The metal quantities released in the soils tested did not appear to pose any environmental hazard, but it could not be determined whether more hazardous quantities could be released from highly contaminated soils.

- **Surface water:** Results indicated that full CMA (acetate) decomposition would occur in 100 days in water at 2°C and much faster in warmer water. Oxygen depletion in water due to biochemical oxygen demand (BOD) from CMA decomposition was found to be a potentially important effect, because CMA concentrations as low as 10 mg/L were associated with reduced oxygen in test ponds. The potential for phosphorus enrichment of surface waters exposed to high concentrations of CMA derived from agricultural products was also reported. Phosphorus enrichment can lead to eutrophication, especially in small, poorly flushed ponds and lakes.

- **Vegetation:** Various applications of CMA to vegetation by spraying and flooding did not affect the yield, cover, vigor, or rooting of various herbaceous and woody plants. All species tested withstood root zone applications of up to 2500 mg/L. This concentration is much higher than expected from routine deicing treatments. Concentrations of 5000 and 10 000 mg/L reduced yield or killed the plants tested.

- **Aquatic biota:** Under varying nutrient regimes in laboratory tests, CMA demonstrated the potential to either inhibit or enhance algal growth, depending on conditions and the algal forms involved. Aquatic invertebrates survived and reproduced in the laboratory at concentrations up to 500 mg/L. They were harmed by osmotic stress and low oxygen at higher concentrations. Fish were resistant to CMA in aerated chambers; hatching and survival were high at concentrations up to 1000 mg/L. Experiments in the test ponds, where concentrations never approached these levels, did not yield detectable effects.

On the basis of these findings, and in anticipation of subsequent full-scale verification, the study provided several interim guidelines for CMA's use. It was concluded that CMA was likely to be safe in most situations, with some possible exceptions. In particular, to avoid extreme concentrations of CMA and oxygen loss in natural waters, the study recommended that CMA not be used near poorly flushed ponds, in catchment areas where highway runoff would not be sufficiently diluted before reaching receiving waters, or when large quantities of CMA could drain beneath the ice cover of receiving waters. In addition, to avoid the possibility of heavy-metal mobilization, it was recommended that use be restricted on highways that might have high metal concentrations in roadside soils or that are near protected surface waters and aquifers used for drinking or inhabited by sensitive water life.

The study indicated that full-scale experiments with actual CMA treatments were needed before permanent use guidelines could be developed.

Other Studies

Several follow-up investigations of CMA's environmental and health-related effects have been conducted during the past few years, including the following:

- Chevron Chemical Company (Hiatt et al. 1988) has studied the short-term toxicity of CMA to humans. Among the tests conducted were oral and inhalation toxicity experiments and eye and skin irritation tests. In addition, highway maintenance workers at several field sites were observed and interviewed after handling CMA. All tests indicated that CMA has low toxicity to humans; however, highway workers at one field site complained of eye and skin irritation. A subsequent investigation indicated that dust exposure levels at the site greatly exceeded the threshold limit for occupational exposure to nuisance dusts, but respirable dust levels were reported to be much lower. The authors concluded that CMA's potential to adversely affect worker health is no greater than that of road salt, but they recommended that standard protective measures, such as exhaust ventilation and dust masks, be observed when working with CMA.

- In work sponsored by the Austrian Federal Ministry for Construction and Technology (Washuttl n.d.), experiments were carried out in laboratories and field plots to determine the effect of CMA on plants. The tests indicated no adverse effects on wheat, rape, and cress. Likewise, high application rates caused no adverse symptoms in exposed spruce, pine, maple, and salt-tolerant shrubs.

- A study conducted in central Alaska tested the effects of CMA on small roadside ponds (Rea and LaPerriere 1986). Three ponds were treated with CMA and three were untreated. The ponds were observed for variations in cation (e.g., calcium, magnesium, sodium, and potassium) concentrations, algal growth, and oxygen levels. Calcium levels were substantially elevated in the CMA-treated ponds, and dissolved oxygen was significantly reduced at times, as predicted by Horner (1988).

- In a follow-up study to Horner (1988), Brenner (1990) compared the effects on surface water of a pure reagent-grade CMA and a CMA product containing organic and inorganic impurities. Results indicated a potential for greater BOD effects from CMA produced from agricultural products than from the reagent-grade CMA, mainly because of the decomposition of organics occurring in agricultural products.

- The effect of CMA on copper and zinc mobility in soils was studied by Elliot and Linn (1987). In tests on acidified (pH 4) soil solutions, CMA initially increased metal mobility; however, this effect was subsequently counteracted by the pH-neutralizing effect of the acetate. On the basis of these findings, the authors concluded that CMA could initially mobilize some soil metals, but that prolonged use would probably inhibit substantial, long-term movement.

- The effect of CMA on soil metals was also investigated by Amrhein and Strong (1990). Roadside soils were collected from around the United States and incubated and leached with CMA and NaCl concentrations likely to be generated by highway deicing. The authors identified three processes that normally cause soil to retain, or immobilize, metals: (a) ion exchange, (b) precipitation from solution with organic compounds, and (c) the formation of complexes with organic matter. Test results indicated that the first process (ion exchange) caused some displacement of trace metals but that the latter two processes offset that effect by impeding metal mobility. As a result, the authors concluded that CMA is likely to have no more effect on metal mobility than NaCl.

- In a study in northern California, water samples were taken from 10 lakes and incubated with various concentrations of CMA to determine effects on phytoplankton growth (Goldman et al. 1990). Eight of the 10 lakes, including Lake Tahoe, showed no significant response in algal growth when CMA concentrations of 0.1, 1, and 10 mg/L were tested. One lake showed a weak stimulation in algal growth at concentrations of 10 mg/L, and one lake showed an inconsistent response, with some growth enhancement at the intermediate concentration of 1 mg/L. The authors concluded that CMA appeared to have negligible effects on phytoplankton growth within the scope of the investigation.

- In a study of CMA's BOD effects sponsored by Chevron (Connolly et al. 1990), experiments indicated that the acetate in CMA degrades rapidly in natural waters. A model of a mixed pond indicated that, for most situations, the use of CMA would have minimal effects on oxygen. The model conservatively assumed no water flow through the pond, no wind enhancement of reaeration, and a CMA-contributing roadway area on the order of one-third the pond area. However, the model did not consider all possible circumstances, such as a body of water in which reaeration is limited by ice cover. The authors noted that under some conditions of ice cover, significant oxygen loss could occur until the ice melts.

Summary of Health and Environmental Evaluations

The only known effect of CMA on humans is its tendency to create a nuisance dust that may require the use of dust masks and well-ventilated storage and handling areas. Studies indicate that CMA is likely to have negligible effects on drinking water. Because it is biodegradable and exhibits poor mobility in soils, it is less likely than

salt to reach groundwater. CMA has demonstrated no detrimental effects on soil compaction or strength, and it may increase the fertility and permeability of some roadside soils. In preliminary environmental evaluations, the potential for CMA to extract heavy metals from soils was identified; however, results from follow-up studies do not indicate this effect.

Neither irrigation nor spraying with CMA has caused detrimental effects in most common roadside plants tested. CMA is apparently safe for use near most aquatic environments, having produced no deleterious effects on organisms representing the aquatic food chain when tested at concentrations likely to be generated by highway deicing. A concern that remains is the potential for CMA to reduce dissolved oxygen levels as it decomposes. Hence, heavy CMA treatments near small, poorly flushed, or poorly diluted ponds and streams may require special monitoring and further study.

These findings may not apply to CMA derived from feedstocks other than reagent-grade chemicals, natural gas, and agricultural products. Alternative feedstocks, such as municipal solid waste and pulp and paper mill biomass, could introduce contaminants that alter its known environmental effects or create new ones.

COMPATIBILITY WITH AUTOMOTIVE AND HIGHWAY MATERIALS

After preliminary environmental evaluations of CMA proved positive, several studies were undertaken to evaluate its impact on automotive and highway materials. Study results are summarized in the following sections.

Automotive Components and Materials

The most comprehensive study of CMA's compatibility with automobiles was conducted by Slick (1987) for FHWA. The study compared the effects of CMA and sodium chloride on common automotive parts, components, and materials. Evaluations consisted of a variety of standard experiments, including immersion dips, spray-fog exposures, and electrochemistry measurements. Among the materials and components tested were paints, primers, and undercoatings; exterior adhesives and plastics; tires and rubber; brake linings; and steels, aluminum alloys, and combined metals, such as chrome, aluminized steel, and nickel-zinc coated steel.

Major findings were as follows:

- **Paints, coatings, and adhesives:** Automotive paints and coatings exposed to CMA exhibited some breakdown, but the same specimens exposed to salt exhibited more severe effects. Neither salt nor CMA affected adhesives.
- **Plastics and rubber:** Specimens of plastic, elastomers, and lens materials were affected similarly by CMA and salt, as were hardness properties and tensile strengths of rubber compounds and tires.
- **Brake systems:** Automotive brake linings exposed to CMA displayed better friction characteristics than specimens exposed to salt. In addition, hydraulic brake line tubes exposed to salt experienced more severe corrosion than specimens exposed to CMA.
- **Metals:** Salt caused more frequent and severe corrosion of automotive steels, aluminum alloys, stainless steels, and combined metals. In particular, pitting and crevice corrosion, which is the principal danger to automotive metals in actual highway conditions, was more prevalent in salt specimens than in CMA specimens.

Results from this laboratory study indicate that CMA is less harmful than salt to most automotive components and materials and much less corrosive to automotive metals. Whether the interactive effects of automobile operating systems and actual highway environments could modify some of these findings has not been studied. The potential for CMA spray to adhere to windshields and body parts, reported by some field users, would probably require further study before more widespread use.

Bridge and Highway Materials

The preliminary laboratory tests of CMA conducted by Dunn and Schenk (1980a) indicated that it would be less corrosive than salt to steel and most other metals commonly used on bridges and highways. Since the initial tests, several studies have been conducted to verify these findings and further evaluate CMA's compatibility with bridge and highway materials.

Bridge Materials

Bridges contain various applications of steel and metals that are susceptible to corrosion, including expansion joints, gutters, railings,

beams, and rebars. A study by the state of Michigan compared the effects of CMA and salt on many of these applications (McCrum et al. 1985). The study consisted of experiments with representative samples of bridge metals (except rebars in concrete), which were exposed to various concentrations of CMA and salt. The results verified earlier findings by Dunn and Schenk (1980a) indicating that CMA was less corrosive than salt. On the basis of weight loss data and general observation, the average corrosion rate of CMA was one-third to one-tenth the corrosion rate of salt for most metals tested. Most CMA specimens exhibited only shallow pitting, compared with deep pitting in salt specimens.

A study by FHWA attempted to determine CMA's effect on rebars in concrete. After comparing reinforced concrete slabs ponded with CMA and salt solutions for 4 years, Chollar and Virmani (1988) found that CMA had no effect on the slabs, whereas salt had significant effects. After 4 years, the slabs ponded with CMA solutions displayed no signs of deterioration, whereas the slabs ponded with salt had many cracks and rust stains. Moreover, whereas the corrosion (electrical) potential of the slabs ponded with salt increased rapidly within the first 3 months of exposure, the slabs ponded with CMA did not show any significant shifts in potential during the 4-year test period.

Additional tests of CMA's compatibility with bridge materials were conducted by Locke and Kennelley (1985) for FHWA. The study consisted of weight-loss and electrochemical measurement tests of bridge metals immersed in solutions of CMA and NaCl. Rebars embedded in concrete (slabs and mortar cylinders) and simulated pore solutions, which were contaminated and ponded with CMA and NaCl, were also tested.

Major findings were as follows:

- Corrosion rates of exposed steel immersed in CMA solutions were one-half to one-fifth those of steel tested in salt solutions, on the basis of weight loss data. The corrosion rates of steel tested in tap water were equal to or slightly higher than those of steel tested in CMA solutions.
- Corrosion of aluminum exposed to CMA was minimal, resembling a passive system. Corrosion rates were $\frac{1}{10}$ those of aluminum exposed to salt, resulting in only slight pitting.
- CMA was much less corrosive to rebars than salt when applied to previously unsalted simulated bridge decks.
- The addition of CMA to simulated pore solutions led to changes in composition, evidenced by a lower pH and a more electronegative

(active) corrosion potential. The authors noted that this effect, if real, might result in an increased rebar corrosion rate when CMA is used on previously salted bridge decks because of the possibility of an increased potential difference between the top rebar mats (exposed to CMA and salt) and lower rebar mats (exposed only to salt).

On the basis of these findings the authors concluded that CMA was likely to be one-half to one-fifth as corrosive as salt to structural steels, one-tenth as corrosive to bridge aluminum, and significantly less damaging than salt to new (uncontaminated) reinforced concrete. They surmised, however, that CMA might accelerate corrosion of reinforcing steel in concrete that has already been contaminated by salt because of the wide variations in electrochemical potential in different areas of the deck. Accordingly, the authors called for additional ponding tests to better determine CMA's effect on the corrosion of rebars in previously salted decks and research on the transport characteristics of CMA to determine how quickly it diffuses into concrete slabs.

FHWA is currently conducting ponding research to determine whether the addition of CMA to previously salted decks accelerates corrosion. Tests are being conducted on rebars embedded in mortar cylinders containing admixtures with varying concentrations of CMA and salt. After 28 days of curing under 100 percent humidity, cylinders of each type were ponded in solutions of salt and CMA. The electrochemical potentials and corrosion currents of the rebars are measured periodically. Results after 500 days were promising; the CMA corrosion potentials measured significantly more passive than reported by Locke and Kennelley (Peart and Jacoby 1991a; Peart and Jacoby 1991b). On the basis of these findings, the FHWA researchers concluded that CMA is not likely to accelerate corrosion of previously salted bridge decks.

In summary, the evidence indicates that CMA is less corrosive than salt to virtually all exposed steels and metals commonly used on bridges for applications such as joints, gutters, railings, and beams. Recent research by FHWA indicates that CMA is less corrosive than salt to rebars in new concrete and will not accelerate corrosion of rebars in chloride-contaminated concrete, as previously surmised. However, there is insufficient evidence to determine whether CMA has a passivating effect (i.e., reduces the rate of corrosion) on concrete that is already contaminated with salt, which is the condition of many older bridges in the snowbelt states of the Northeast and Midwest (see Chapter 3).

Other Highway Materials

The most comprehensive investigation of CMA's compatibility with highway materials was conducted by Slick (1987) for FHWA. The study examined CMA's effect on portland cement concrete, asphalt, paints, adhesives, joint sealants, drainage pipes, and sign sheetings. Tests performed included concrete compression, abrasion, and scaling-resistance tests; static loading and impact tests; and friction, adhesion, and hardness evaluations.

Major findings were as follows:

- **Pavement materials:** The compression strengths of portland cement concrete and asphalt products were not affected by either salt or CMA. Scaling did not occur in any asphalt products; however, some scaling occurred in portland cement concrete. Scaling was more severe in salt specimens than in CMA specimens. Roughly the same pattern of scaling occurred on joint sealant specimens.
- **Road-marking materials:** Road-marking materials, such as paints, plastics, and tape, were affected by both salt and CMA. Specimens exhibited chalking, erosion, and flaking. In all cases, however, specimens exposed to salt were damaged more severely than specimens exposed to CMA.
- **Construction materials:** The hardness properties and impact resistance of bridge-bearing materials were not affected by either salt or CMA. Crushing strengths of concrete, corrugated metal, and plastic pipes were also not affected by either deicer.

In follow-up work sponsored by the Ontario Ministry of Transportation, Pianca (1987) tested the scaling properties of salt and CMA on typical concrete mixes used in Ontario. The study findings indicated that good-quality new concrete was resistant to scaling by both salt and CMA, but that the scaling was more severe in poor-quality new concrete exposed to salt.

Summary of Compatibility with Automotive and Highway Materials

CMA is much more compatible with automotive parts than salt. Virtually all automotive materials and components tested have exhibited fewer negative reactions when exposed to CMA than when exposed to salt. The tendency of CMA spray to adhere to windshields

and body parts, which has been reported by some field users, would probably require further study before more widespread CMA use.

Laboratory tests also indicate that CMA is less detrimental than salt to common highway materials, including those used for paving, road marking, and construction. CMA is also less corrosive than salt to exposed steel and other metals commonly used on bridges for applications such as joints, gutters, railings, and beams. Recent findings indicate that CMA is less corrosive than salt to new reinforced concrete and does not accelerate corrosion of older, chloride-contaminated concrete. However, there is insufficient evidence that CMA reduces the rate of corrosion of steel in concrete that is already contaminated with chlorides, which is the condition of many older bridges in the Northeast and Midwest.

PRODUCTION TECHNOLOGIES AND PRICE

CMA is produced by reacting dolomitic lime with acetic acid. The resulting solution is dried and processed to obtain the final product. Except for expensive food-grade applications (such as vinegar),⁶ acetic acid is usually derived from natural gas, which is CMA's chief cost component.

Attempts have been made to reduce CMA's production costs by exploring alternatives to natural gas. Soon after CMA's discovery, Marynowski et al. (1983), under contract with FHWA, surveyed acetate production technologies. The authors and FHWA concluded that a bacteriological fermentation process would yield the least expensive acetic acid. Preliminary process designs and economic analyses indicated that the fermentation process would lower CMA production costs by between \$300 and \$400 per ton if corn were used as a feedstock for fermentation.⁷ Subsequent work by researchers at the University of Georgia (Ljungdahl et al. 1986) led to the production of CMA by this process. An economic evaluation of the process, however, indicated that production costs (not including shipping) would be on the order of \$500 per ton, which is not significantly different from costs associated with the natural gas process.

Recently, Dynatech Scientific, Inc., under contract with the New York State Energy Research and Development Authority (NYSERDA) and several cosponsors, has explored fermentation processes using regional industrial and agricultural wastes (Leuschner 1988). The objective of the research is to develop processes for using locally generated waste materials. Feedstock sources considered include agricultural residues, such as grape and apple pomace, and industrial

wastes, such as dairy whey and pulp and paper mill sludges. Preliminary engineering and economic analyses based on the use of dairy whey as a feedstock projected an ultimate CMA price of \$280 per ton (Leuschner 1988).⁸

NYSERDA is also considering woody biomass (such as paper and pulp mill waste) as a possible feedstock, because it is available in much larger quantities than most other organic wastes (Wise and Augenstein 1988; DeSouza and Wise 1991). Significantly more work is required before initial cost projections for this process can be substantiated with actual production costs (personal communication with NYSERDA project manager). Other processes for using waste material, including municipal solid waste, have recently been considered by Trantolo et al. (1991). However, the potential environmental effects of these processes, resulting from the introduction of impurities into CMA, have not been adequately evaluated.

In a study sponsored by the Ontario Ministry of Transportation, Sheridan Technical Associates (1990) reviewed various technologies for CMA production. On the basis of economic evaluations of capital and operating costs for the most promising technologies, the authors estimated that CMA could be produced at a cost of approximately \$300 per ton by using municipal solid waste as a source of energy for acetic acid production. The cost estimates, however, assume production of 1 million tons of CMA per year.

Chevron Chemical Company, the only major producer of CMA, uses acetic acid derived from natural gas. Chevron produces CMA for highway agencies that use it on a selective basis. In anticipation of greater demand for CMA in the future, Chevron sells it for \$600 to \$700 per ton (delivered). These prices are intended to cover full-scale production costs if CMA were sold in much larger quantities (personal communication with Chevron deicing products representatives).

Highway deicing is the primary market for CMA, but attempts are being made to find other markets. Chevron recently began marketing CMA as a deicer on airport runways and parking garages and as a dust-control chemical for dirt and gravel driveways (personal communication with Chevron deicing products representative). Potential use of CMA as an additive in coal-fired furnaces (such as those used by electric utilities) to facilitate combustion and remove sulfur from emissions has been explored (Wise et al. 1991). There is not yet sufficient evidence to determine whether these applications will be economically successful or will have a significant impact on the price of CMA used for highway deicing.

NOTES

1. Environmental concerns about methanol include its potential volatility during handling and storage and its lethality to humans and animals if ingested.
2. The relationship is based on the requirement (for ideal solutions) of equal concentrations of ions from NaCl and from CMA for the same lowering of the freezing point.
3. In addition, CMA is being or has been used in locations in Pennsylvania, Tennessee, Arkansas, Louisiana, Minnesota, Arizona, Winnipeg, Atlanta, and Oklahoma.
4. CMA does not dissolve as readily as NaCl, thereby slowing initial action. In addition, because the ions in CMA are larger than those in NaCl, the rate of diffusion into the liquid film surrounding ice is slower, which further delays CMA's reaction time compared with NaCl.
5. Calcium and various acetates are sometimes used to extract metals from soils in chemical reactions. Metal automotive parts, radiator fluid, tire compounds, fuel, and emission from traffic contribute to heavy-metal contamination in roadside soils.
6. Vinegar is created using an aerobic fermentation process.
7. Corn was chosen as a feedstock partly because it is grown in virtually all regions of the country.
8. Unlike corn grain and paper mill waste, which require treatment before fermentation, dairy residues are already in a form that allows for direct fermentation. NYSEERDA initially selected dairy whey as the preferred feedstock because of this advantage (Wise and Augenstein 1988, 455).

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ABBREVIATIONS

FHWA	Federal Highway Administration
NCHRP	National Cooperative Highway Research Program
TRB	Transportation Research Board

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7

Summary of Cost and Use Issues



Findings from Chapters 3 through 5 on the adverse side effects of road salt are summarized in this chapter. That discussion is followed by a review of what is known about the effects of calcium magnesium acetate (CMA) as a highway deicer, as summarized from

Chapter 6. The chapter concludes with a new section, drawn from findings in previous chapters, covering cost and use issues that must be addressed when considering CMA as a replacement for salt.

ROAD SALT COSTS

Each year about \$1.5 billion is spent on highway snow and ice control. Chemical deicing accounts for about one-third of this expense. Sodium chloride, or common road salt, is by far the most widely used deicer, accounting for about 95 percent of deicer treatments. The only other significant deicer is calcium chloride, which is often mixed with salt during colder temperatures. It accounts for about 5 percent of chemical treatments.

Over the years, evidence has grown linking the two most popular chemical deicers—sodium chloride and calcium chloride—with many adverse side effects, including corrosion of motor vehicles and infrastructure, damage to the roadside environment, and contamination of drinking water.

Motor Vehicle and Infrastructure Costs (Chapter 3)

Sodium chloride, as well as calcium chloride, can damage motor vehicles and infrastructure primarily because of the corrosive effects of chloride ions on metals. The chloride ions in salt disrupt natural protective films on metal surfaces and increase the conductivity of water, which induces and accelerates electrochemical corrosion. The best-known side effect of salting is corrosion of automotive metals and rebars in bridges and parking structures. Lesser-known effects, which collectively may be significant, include damage to reinforced pavements and metal highway fixtures; corrosion of underground utilities, pipelines, and steel storage tanks; and degradation of metal objects located on or alongside salt-treated highways.

Motor Vehicles

Motor vehicles have suffered from more severe corrosion since the introduction of road salt following World War II. From the 1950s to the 1970s, the increased use of salt and calcium chloride, combined with the effects of acid precipitation (e.g., acid rain, snow, and dew) greatly increased the corrosivity of the highway environment. The corrosivity of the environment peaked in the 1970s and resulted in widespread rusting of vehicles in the Northeast and Midwest.

During the past 20 years, automobile manufacturers have developed more corrosion-resistant vehicles by improving automotive designs, materials, and manufacturing processes. Improvements include the extensive use of precoated steels, plastics, new primer and coating materials, and modified body configurations that eliminate salt entrapment areas. Today's cars and trucks are less vulnerable to corrosion than vehicles built 10 to 20 years ago. This corrosion protection, however, has increased the cost of manufacturing motor vehicles. On the average, the special materials and coatings used to improve corrosion resistance have added about \$500 to the price of a new vehicle.

Only a portion of this expense can be directly attributed to road salt. Other important reasons for protection include acid precipitation, salt spray in coastal areas, and calcium chloride used for dust control. It is likely that even the complete elimination of road salt would result in only partial reductions in corrosion protections and their cost. Estimates by manufacturers suggest that road salt accounts for between one-fourth and one-half of protection costs, or about \$125 to \$250 per vehicle (0.25 to $0.50 \times \$500$). The total annual cost

for the more than 15 million new vehicles purchased each year in the United States is between \$1.9 billion and \$3.9 billion (15.4 million new vehicles \times \$125 to \$250).

The primary type of corrosion that persists today is cosmetic corrosion, which is far less damaging than the structural and functional corrosion of the 1970s. Nevertheless, cosmetic corrosion continues to concern motorists in the Northeast and Midwest, where time and money are spent to prevent it and resultant losses in vehicle value and appearance. Preventive efforts include aftermarket rustproofing (which is fast declining in popularity as rust protection during manufacture continues to improve), more vigilant repair of paint damage, and more frequent car washing and other exterior maintenance.

Data are inadequate to reliably quantify preventive maintenance costs or losses in vehicle values due to persistent corrosion. Nevertheless, these costs are likely to be large. A rough estimate to determine an order of magnitude can be developed on the basis of the amount that new car buyers might be willing to spend to eliminate persisting corrosion. If motorists in salt-using regions of the Northeast and Midwest—where 9 million new vehicles are purchased each year—were willing to spend \$125 to \$250 per new vehicle (a plausible range that is equivalent to the cost of existing salt protection features), this cost item alone would be between \$1 billion and \$2 billion per year (9 million new vehicles \times \$125 to \$250).

Bridges

The condition of the nation's highways has received intense public and legislative attention during the past 20 years. In the snowbelt states, much of the attention has focused on maintenance and repair problems associated with the use of salt on bridge decks. Salt is especially damaging to decks because the chloride ions in salt, along with moisture, penetrate concrete and cause the rebars to rust, which results in cracking and fragmenting of the surrounding concrete. The damaged areas provide access to additional salt, which accelerates the destructive process. The damage seldom affects the structural integrity of the deck, but it can cause extensive potholing of the deck surface, which can degrade ride quality.

Most decks built within the past 10 to 20 years are equipped with some type of protection to prevent salt penetration and rusting of rebars. Protective systems include waterproof membranes, thicker and denser concrete overlays, and epoxy coating of rebars. To date, deck protection has succeeded in reducing salt damage. However, it

has increased the cost of constructing a new deck by about \$4/ft². Between 20 million and 30 million ft² of new deck surface is constructed each year in the Northeast and Midwest; hence, annual spending on deck protection is about \$75 million to \$125 million (\$4/ft² × 20 to 30 million ft², rounded to the nearest \$25 million).

Thousands of decks built during the 1950s and 1960s are now contaminated with chlorides and are deteriorating. Repair and restoration of these decks as they become deficient will be a major expense for many years. However, because they are already contaminated with salt and the corrosive process is well under way, further exposure to salt (or noncorrosive deicers) is likely to have little effect. A more urgent concern is to prevent damage in newer decks that are not already contaminated with salt. Because the many newer decks built during the past 20 years are well protected against salt damage, they should experience fewer adverse effects from road salt than older decks. Even state-of-the-art protection, however, may not completely control corrosion.

A plausible estimate of the number of decks that will become damaged during the next 10 years because of continued salting is 3,500 to 7,000—representing some 25 million to 50 million ft² of deck surface. The average cost of rehabilitating a deck is \$20 to \$40/ft². If about $\frac{1}{10}$ of the damaged decks must be restored each year during the 10-year period, the total cost will be between \$50 million and \$200 million per year ($\$20 \text{ to } \$40/\text{ft}^2 \times \frac{1}{10} \times 25 \text{ million to } 50 \text{ million ft}^2$).

The total cost of installing protection on new decks (\$75 million to \$125 million) and restoring sound decks that become damaged by continued salting (\$50 million to \$200 million) will be roughly \$125 million to \$325 million per year during the next 10 years.

Other components of bridges vulnerable to salt damage include steel framing, bearings, joints, and structural elements made of reinforced concrete. These components can be exposed to salt from leaky decks, faulty drainage, and splash and spray from roadways. The condition of these other components is also affected by factors other than road salt. Compared with deck damage, however, damage to structural elements can be especially difficult and expensive to repair. Although the data available to estimate these costs are limited, the committee believes that collectively they may be as large as deck costs and, as a rough approximation, fall within the same range of \$125 million to \$325 million per year.

Other Highway Components

Apart from bridges, components of the highway system adversely affected by road salt include concrete pavements, highway drainage systems, and roadway fixtures and accessories (such as metal light stands, signposts, and guardrails). Whereas salt is clearly a factor in bridge durability, its impact on other highway components is incremental and, therefore, difficult to isolate and quantify. Most highway components deteriorate or become obsolete for reasons related to the quality of original construction, maintenance practices, and the environment in which they are located. For instance, important factors affecting durability and replacement of highway fixtures are vehicle collisions, traffic vibrations, vandalism, and functional obsolescence. On the basis of the limited available evidence, the committee believes that salt damage to highway components is sizable but probably an order of magnitude smaller than total bridge costs—totaling less than \$100 million per year.

Parking Garages

There are about 5,000 multilevel parking garages in the Northeast and Midwest. Many were built during the 1960s and 1970s, when concerns about salt-related corrosion were minimal. Hundreds of these structures have become contaminated and damaged by salt dropped from parked cars during the past 20 years. The process is similar to that of bridge decks. The chloride ions from salt, along with moisture, seep into the reinforced concrete slabs, reach the embedded steel, and induce corrosion.

Many garages built before the 1970s in heavy salt-using regions are already critically contaminated with chlorides and will need to be repaired (or in some cases demolished) regardless of future salt use. The average cost of restoring a single multilevel garage is about \$1 million. On the basis of assumptions about the number of vulnerable garages that were constructed during the 1970s, the committee estimates that between 500 and 1,500 will become damaged by continued salting during the next 10 years. If $\frac{1}{10}$ of these structures must be restored each year for the next 10 years, the annual cost will be \$50 million to \$150 million (0.10×500 to $1,500 \times \$1$ million).

As a precaution against salt damage, many of the approximately 200 parking garages constructed each year in salt-using regions of

the United States are equipped with some type of protective system, such as epoxy-coated rebars and a denser and thicker concrete cover. The total cost of installing protection on new parking garages is about \$25 million per year. Total parking garage costs from road salt are therefore between \$75 million and \$175 million per year.

Underground Objects

Corrosion damage to utility lines, pipelines, and steel storage tanks buried under or alongside highways is sometimes linked to the use of road salt, especially in urban areas with a high density of underground utility lines and heavy salt usage.

Most incidents of salt damage to underground objects are reported by water and electric utilities. Newer pipelines and cables are protected from corrosion by special coatings, insulation, or cathodic protection, but salt can damage older lines and other buried equipment, such as transformers, switches, and valve components. Quantification of the damage is difficult because of the presence of other corrosion-causing factors. Corrosion, in general, is a leading cause of failures in pipelines. Pipeline operators and utility companies spend millions of dollars each year monitoring corrosion, applying cathodic protection and special coatings, and repairing corrosion damage. Even if only a small fraction of this spending is related to road salt, the resultant cost could be large.

Another potentially significant, although highly uncertain, effect of salt concerns fuel storage tanks buried under gas station service yards. Corrosion of these tanks has become a major environmental concern during the past 10 years. Thousands, containing petroleum and other hazardous chemicals, have been leaking into surrounding soil and groundwater. Road salt is continually tracked into gas station service yards and is considered one of many factors contributing to the problem. Because removal and cleanup of corroding tanks is expected to cost several hundred million dollars during the next decade, even minor contributions by road salt could have important cost implications.

Roadside Objects

Road salt can adversely affect nonhighway objects located along the roadside. For instance, salt can contribute to the corrosion and degradation of bronze statues, monuments, and copper roofing that are

exposed to traffic-generated salt splash and spray. Because the severity and extent of damage depend on local circumstances—such as salt usage, the number of roadside objects, and the presence of other corrosion sources—it is not possible to quantify this damage on a national basis. Salt damage may be significant in some locations, especially if irreplaceable artistic or historic works are involved.

Summary of Motor Vehicle and Infrastructure Costs

The committee's estimate of annual motor vehicle and infrastructure costs from road salt were summarized in Table 3-9. Cost items that can be reliably quantified appear in Category I. Their total suggests a minimum indirect cost ranging from about \$2 billion to \$4.5 billion per year. Inclusion of other items, for which limited supporting data are available, results in a less precise but more complete estimate of about \$3.5 billion to \$7 billion per year.

Impacts on the Environment (Chapter 4)

The literature documenting the impacts of road salt on the environment indicates that they can be significant but depend on many site-specific factors, such as the timing and quantity of salt applied, local drainage features, weather conditions, soil type, topography, watershed size, vegetation cover and species composition, and distance from the roadway. In addition, there is likely to be an interaction between salt and other environmental perturbations, such as vehicle exhaust emissions, drought, and plant diseases and pests. Hence, findings from each study must be reviewed in the light of prevailing conditions at the particular site. The only generalization that can be made is that road salt's impacts tend to diminish rapidly with distance from the roadway.

Environmental impacts most frequently cited in the literature are damage to roadside vegetation, soil, and surface water.

Vegetation

Trees and other roadside vegetation, such as shrubs and grasses, can be harmed by salt or other chloride deicers through changes in soil chemistry and splash and spray on foliage and branches. The symptoms of salt injury in trees are similar to those of drought: inhibited

growth, browning and falling needles and leaves, and sometimes dying limbs and premature plant death. Under extreme conditions (e.g., high winds), roadside trees can be exposed to salt spray as far as 500 ft from the roadway, although this impact is seldom significant beyond 100 ft. Damage to trees is likely to be greatest along **high**-traffic highways with heavy salt use and steep, downsloping roadsides. Highway agencies in states where public concern about tree damage is greatest report that 5 to 10 percent of the trees along some sections of heavily traveled highways show symptoms of salt-related decline. Common roadside shrubs and grasses tend to tolerate salt better than do trees, and most states report only minor damage to these plants.

It is difficult to quantify damage to roadside vegetation. Information derived from highway agency interviews and composites of many case studies illustrate the cost of mitigating some of the effects. For example, estimates from state highway agencies indicate that the cost of removing and replacing a damaged tree is \$500. Hence, in a 1-mi corridor of highway containing 1,250 to 3,500 trees per mile (within 100 ft of the roadway), in which 5 to 10 percent of the trees must be removed and replaced over a 10-year period, the average mitigation cost would be \$3,000 to \$18,000 per year (0.05 to $0.10 \times 1,250$ to $3,500 \times \$500 \times 0.10$).

Soil

Salt's effects on soils are usually confined to 15 ft from the pavement. The primary concern is long-term sodium accumulation, which can adversely affect soil structure characteristics. Specifically, sodium accumulation can increase soil density and reduce permeability, moisture retention, and fertility, which are important to plant growth and erosion control. However, whether salt has a cumulative effect depends on local conditions, such as soil type, precipitation, and topography.

Where salt severely alters soil structure and reduces essential nutrients, reclamation of the affected soil is an option. The primary objective of soil reclamation is to increase infiltration and moisture retention capabilities. The average cost of reclaiming damaged soil is about \$650 per acre. Where soil damage also results in erosion problems, additional erosion control may be necessary. Erosion may be caused by numerous interrelated factors, and the cost of erosion control always depends on circumstances unique to the site.

Surface Water

Salt's effects on surface water are confined mainly to small streams and creeks running adjacent to heavily salted highways. Small receiving lakes and ponds can also be adversely affected, but few such incidents have been reported. In general, salt loadings in larger rivers and lakes are diluted because of high water volumes. In extreme cases, salt concentrations in streams can harm fish and other stream life. The complexity of stream environments, however, makes it difficult to characterize and quantify potential adverse effects.

Summary of Impacts on the Environment

Consolidation of the many site-specific environmental impacts of road salt into a national estimate of salt damage is not possible. Monetary evaluations have been attempted to shed light on the importance of environmental damage. Whereas these efforts have led to increased recognition of salt's effects, they were not intended, nor can they be accurate enough, to compare the overall cost of salt with that of other deicing options. Meaningful estimates of environmental cost can be accomplished only for individual sites by evaluating local circumstances in depth.

Even when environmental damage can be quantified for a specific site (e.g., the number of trees injured along a highway section), a monetary value can be difficult to assign. Estimates of mitigation costs—for example, the cost of removing and replacing an injured tree—provide some cost perspective, but they may be inaccurate or incomplete because they do not reflect the value of the injured tree to society or indirect costs, such as diminished aesthetics and secondary effects on the roadside ecosystem.

Drinking Water and Health Impacts (Chapter 5)

Road salt can enter drinking water supplies by migrating through soil into groundwater or by runoff and drainage directly into surface water. In general, only wells or reservoirs near salt-treated highways or salt storage facilities are susceptible to salt infiltration. Susceptibility depends on many factors, such as salting intensity, soil type, climate, topography, and water volume and dilution. Other sources of salt include natural brines and salt deposits, industrial and agricultural chemicals, and water treatment and softening processes.

During the past 30 years, communities in several states, primarily in the Northeast, have reported higher sodium and chloride concentrations in private wells and public water supplies that have been linked to road salt. Many of these problems have been caused by improper salt storage. Most of the more egregious storage problems are now being corrected. Some communities continue to report salt concentrations in water supplies due to highway surface runoff, although such concentrations are seldom as high as those associated with improper salt storage.

The discovery of higher salt concentrations in drinking water due to road salt has raised concerns about possible adverse effects on public health. Salt is a source of sodium in the diet. Excess dietary sodium has been negatively associated with health primarily because of concerns related to hypertension, or high blood pressure. Typically, drinking water and all other beverages combined (which tend to have much higher concentrations of sodium than drinking water) account for less than 5 percent of daily sodium intake. Because of the normally minor contribution of drinking water to sodium intake, no federal standards have been established for salt (i.e., sodium or chloride) concentrations in water supplies.

Efforts to mitigate the amount of salt in drinking water vary by state and community. Mitigation may include modification of highway drainage, relocation of private wells, upgrading of storage facilities, and reduced salting near water supplies. Nationally, about \$10 million is spent each year on mitigation by state and local governments, mostly in the Northeast and Midwest.

CMA

In 1980 the Federal Highway Administration (FHWA) identified CMA as a potentially suitable replacement for salt. Numerous laboratory and field studies have been conducted during the past decade to evaluate its field performance, environmental and health effects, compatibility with automobile and highway materials, and production cost. Findings from completed studies and interviews with CMA field users are summarized in the following sections.

Field Experience

Although reports are not always consistent, experiences of CMA users provide some general insights into CMA's field performance

relative to salt. Most users reported that it worked adequately but not quite as effectively or in quite the same manner as salt. Unlike salt, it did not produce significant surface melting and flowing brines that melt ice from top to bottom. CMA worked best when applied at the outset of a storm, before significant snow and ice accumulation. When applied early, it was able to mix with the falling snow and prevent the formation of snowpack and the bonding of ice to the pavement. It performed best when accompanied by plowing or traffic activity, which was important for removing loose snow and ice from the pavement. In situations characterized by light traffic and limited plowing or when ice and snowpack were allowed to accumulate, its performance was often reduced. Whereas salt also worked best when accompanied by traffic and plowing, its ability to produce surface melting made traffic activity and early application less important factors.

Users also reported that CMA performed somewhat less effectively than salt at lower temperatures and in certain types of storm conditions. Although slightly slower acting, its performance was comparable with salt's at storm temperatures above -5°C (23°F).¹ At these temperatures, it started to penetrate light snowpack within 15 to 30 min of salt (salt acted almost immediately). When used during colder conditions, however, CMA's relative effectiveness diminished. For instance, at storm temperatures between -10°C and -5°C (14°F and 23°F), its performance was frequently judged inadequate. It was also described as less effective than salt during freezing rain and storms characterized by light, fluffy snow.

Most users indicated that between 20 and 70 percent more CMA than salt was required during the winter. Spreader units were typically calibrated to release about 50 percent more CMA than salt, although CMA was often applied less frequently during longer storms. Several highway agencies found that early application (i.e., at the outset of the storm, before significant accumulation) was critical and helped improve its effectiveness and reduce the amount used. As might be expected, highway agencies with the most experience using CMA developed more effective and efficient use strategies that helped reduce application quantities over time.

The general conclusion reached by most users was that CMA's handling and spreading characteristics are comparable with those of salt. No major problems were identified. The most frequently cited drawback was its tendency to cake and stick to spreading equipment, which required operators to periodically chip or knock loose accumulations between applications and during cleanup. Generally, however, this problem was described as only a minor inconvenience. The

field reports indicate that dusting and blowing were less troublesome than reported in pre-1985 field trials, though in many cases protective dust masks and truck covers were still required during handling and spreading activities.

CMA had to be kept dry during storage, usually in enclosed and well-ventilated shelters. Because most tests were conducted using small quantities, users could not project storage requirements for prolonged and large-scale use. CMA is less dense than salt, taking up about 60 percent more space per ton. As a practical matter, therefore, the effect of large-scale use on existing storage and truck capacities is likely to be an important consideration to users. On the basis of product density differences alone (not including differences in tonnage requirements), at least 60 percent more storage and truck capacity would be required if CMA is used as a more general replacement for salt.

Health and Environmental Effects

The only known effect of CMA on humans is its tendency to create a nuisance dust during storage and handling that may require the use of dust masks and well-ventilated storage and loading areas. Studies indicate that CMA is likely to have negligible effects on drinking water. Because it is biodegradable and exhibits poor mobility in soils, it is less likely than salt to reach groundwater. CMA has demonstrated no detrimental effects on soil compaction or strength, and it may increase the fertility and permeability of some roadside soils. In preliminary environmental evaluations, the potential for CMA to extract heavy metals from soils was identified; however, results from follow-up studies have not indicated this effect.

Neither irrigation nor spraying with CMA has caused detrimental effects in most common roadside plants tested. CMA is apparently safe for use near most aquatic environments, having produced no deleterious effects on organisms representing the aquatic food chain when tested at concentrations likely to be generated by highway deicing. A concern that remains is the potential for CMA to reduce dissolved oxygen levels as it decomposes. Hence, heavy CMA treatments near small, poorly flushed, or poorly diluted ponds and streams may require special monitoring and further study.

These findings may not apply to CMA derived from feedstocks other than reagent chemicals, natural gas, and agricultural products. Alternative feedstocks, such as municipal solid waste and pulp and

paper mill biomass, could introduce contaminants that alter its known environmental effects or create new ones.

Compatibility with Motor Vehicles and Highway Materials

CMA is much more compatible with automotive materials and components than is salt. Virtually all automotive metals, materials, and components that have been tested in laboratory experiments have exhibited fewer negative reactions when exposed to CMA than when exposed to salt. The tendency of CMA spray to adhere to windshields and body parts, which has been reported by some field users, would probably require further study before more widespread CMA use.

Laboratory tests also indicate that CMA is less detrimental than salt to common highway materials, including those used for paving, road marking, and construction. CMA is also less corrosive than salt to exposed steel and other metals commonly used on bridges for applications such as joints, gutters, railings, and beams. Most recent findings indicate that CMA is less corrosive than salt to new reinforced concrete and does not accelerate corrosion of older, chloride-contaminated concrete. However, there is insufficient evidence to determine whether CMA reduces the rate of corrosion of reinforced concrete that is already contaminated with chlorides, which is the condition of many older bridges in the Northeast and Midwest.

Production Costs and Price

CMA is produced by reacting acetic acid with dolomitic lime. Whereas dolomitic lime is abundant and inexpensive, acetic acid is far more costly. Currently, the most economical method of producing acetic acid is by using natural gas as a feedstock. After spending several years investigating alternative processes for producing CMA, FHWA and most states now rely on industry for further development.

Chevron Chemical Company is currently the only commercial producer of CMA. It makes a pelletized product in which the acetate is derived from natural gas. The current price is \$600 to \$700 per ton delivered to reflect projected full-scale production costs. Various technologies have been explored during the past 10 years to produce CMA less expensively, but no significant breakthroughs appear imminent. Given the uncertain prospects of alternative production technologies and the long-term schedules required to introduce new

production processes, CMA prices on the order of \$600 to \$700 per ton are the only reasonable projections that can now be made.

COST AND USE ISSUES

As a means of identifying some of the important cost and use issues that must be addressed when considering conversion to CMA, three general situations are discussed. First, the use of CMA on a widespread, or systemwide, basis is considered. This is followed by a discussion of a local conversion to CMA, such as in a state maintenance district or in a municipality. Finally, consideration is given to highly selective CMA application, which is essentially how CMA is used today.

Widespread CMA Use

The main reason for considering a large-scale conversion to CMA is to reduce all or most of the indirect costs of salting. Use of CMA as a general replacement for salt would probably result in sizable reductions in certain salt-related damages, such as corrosion of inadequately protected motor vehicles, bridges, parking structures, and roadside objects.

As a practical matter, however, large-scale conversion to CMA would have uncertain effects on many costs related to corrosion protection. For example, in the case of motor vehicles, the continued corrosivity of the highway environment due to atmospheric pollution (e.g., acid precipitation), sea spray, and other highway contaminants would probably result in only partial reductions in vehicle rust protection and its cost. Moreover, if the highly corrosive chemical calcium chloride is still used in large quantities for low-temperature deicing (at temperatures in which CMA is not an effective alternative) and for dust control, manufacturers might forego little, if any, corrosion protection, even in the complete absence of road salt. For similar reasons, widespread use of CMA would result in uncertain effects on corrosion protection of new bridges and parking structures. The abandonment of corrosion protection on new structures (which are designed for 40 or more years of service) would be risky, because of the existence of other corrosion sources and the potential for salt or calcium chloride to be used on the structure in the future (if, for example, funding for CMA was no longer available or CMA was not effective for all deicing conditions).

Widespread use of CMA would benefit aspects of the roadside environment and possibly the quality of drinking water in some communities. Most research indicates that CMA has less severe impacts than salt on the environment and water quality except in certain controllable situations. Because the effects of road salt on the environment depend on the specific site, it is difficult to estimate the specific environmental savings, or benefits, that might be achieved from the general use of CMA.

If a moderate- or large-scale conversion to CMA were made, highway agencies would learn how to use CMA more efficiently and effectively. They would modify equipment and adopt spreading, handling, and storage practices better suited to CMA. Nevertheless, such a conversion would have far-reaching effects on winter maintenance budgets and operations, both during the initial conversion and in the long term. Widespread use of CMA would present operational challenges to highway agencies that are accustomed to salt's greater versatility and better ice-melting capacity. For instance, a potential drawback to widespread CMA use is the need to apply it early during a storm. Highway agencies typically treat primary highways first and secondary roads later, after snow and ice has accumulated. Because CMA is less effective when application is delayed, earlier treatment of all roads might be necessary.

Currently, state and local highway agencies spend about \$300 million to purchase the 10 million tons of salt that is spread each winter (Chapter 2). This expenditure, which does not include attendant spreading, handling, and storage costs, represents about one-fifth of the \$1.5 billion spent each year on highway snow and ice control. Priced at about \$650 per ton, CMA is about 20 times more expensive per ton than salt, which sells for an average of about \$30 per ton. The experience of CMA users suggests that at least 20 percent more CMA is required than salt (by weight) during the winter. Accordingly, complete replacement of salt by CMA would result in approximately a 25-fold increase in deicing material costs (1.2 times more CMA tonnage \times 20 times higher price per ton). Total spending on deicing material would increase from \$300 million to about \$7.5 billion per year ($25 \times \$300$ million).

By itself, a 25-fold increase in deicing material costs would increase total spending on winter maintenance (\$1.5 billion per year) by a factor of about five ($\$7.5$ billion/ $\$1.5$ billion = 5). Additional storage space and spreading equipment, as well as changes in deicing practices, would increase expenditures even more, particularly during the initial conversion. CMA is less dense than salt, requiring 60 percent more storage space per ton. This density difference combined with

CMA's greater quantity requirements suggests that nearly twice as much storage space and truck capacity would be required (1.2 times more CMA tonnage \times 1.6 times greater volume per ton = 1.92 times more volume per ton of salt replaced). This requirement would translate into additional spending on enclosed storage facilities, spreading equipment, and manpower. As an illustration of the potential magnitude of these costs, the New York State Department of Transportation estimates that existing salt spreading, handling, and storage operations cost about \$25 per ton of salt applied and represent about 15 percent of state expenditures on highway winter maintenance (see Chapter 2). A near doubling of these costs would increase existing winter maintenance budgets by 10 to 15 percent.

Local CMA Use

Conversion to CMA on a more limited basis (i.e., a municipality or state highway district) would probably result in some savings in salt-related damage in locations where CMA is used, although not in proportion to the reduction in salt use (e.g., a 10 percent reduction in salt use would probably result in a much smaller reduction in salt-related costs).

The main reason for using CMA in this manner would be to reduce local environmental and infrastructure damage from salt. Local environmental effects and possible savings can only be determined on a site-by-site basis. Local conversion to CMA, however, would result in little, if any, savings in vehicle corrosion and protection costs, because vehicles would still be exposed to salt elsewhere, and relatively small amounts can cause corrosion (see Chapter 3). Local CMA use would probably result in some savings in damage to bridges and other infrastructure. The savings would depend largely on the level of protection and the condition of infrastructure in the locality where CMA is applied. For example, application on bridge decks that are sound and poorly protected from salt might result in sizable reductions in corrosion damage, whereas application on well-protected or salt-contaminated bridges would have less beneficial results. In all likelihood, the savings from reduced salt protection on new bridges and parking garages would be negligible, because of salt-tracking from non-CMA areas and the possibility of salt or calcium chloride being used in the future.

Many of the operational and budgetary issues associated with a local conversion to CMA are similar to those identified in the preceding discussion of widespread use. Highway agencies would be

challenged by CMA's limited versatility compared with salt. Considerably more spending on deicing material, equipment, and manpower would be necessary even for local use. For example, a 10 percent conversion to CMA by a state highway agency would increase its total expenditures on deicing material by about 2.5-fold because of CMA's higher price and greater volume requirements (0.10×25 -fold increase in deicing material costs estimated for widespread use).

By itself, a 2.5-fold increase in deicing material costs, which normally account for about 20 percent of winter maintenance budgets, would increase state spending on snow and ice control by about 50 percent (0.20×250 percent). However, conversion to CMA would also require modification of storage, handling, and spreading operations and equipment. Estimates from the previous discussion on widespread CMA use suggest that existing spreading, handling, and storage costs would nearly double in locations where CMA is widely used.

Selective CMA Use

Currently, CMA is used selectively and in small quantities, primarily in environmentally sensitive areas and on new (uncontaminated) concrete structures and highway sections. On the basis of existing information about CMA's deicing performance and cost, the committee believes that such selective applications are likely to be the principal uses for CMA in the future.

Whether CMA should be used in such situations can only be determined on a case-by-case basis, after comparing salt, CMA, other deicers, and other mitigation measures. This is especially true for environmentally sensitive areas, because each roadside has its own unique environment, and valuations of environmental damage vary by location. For instance, CMA is currently used on highway sections in California and Nevada to reduce chloride injury to roadside trees and in Massachusetts to prevent sodium contamination of residential wells. In each of these states, the decision to use CMA was influenced more by public pressure than economic evaluations of the total costs of each product.

Similarly, whether it is appropriate to use CMA on a specific bridge or highway segment to reduce corrosion damage can only be determined on a case-by-case basis. To illustrate some of the factors that must be evaluated by highway agencies when considering the use of CMA, three hypothetical bridge examples are presented in

Table 7-1. Numerous assumptions are required, including the timing and cost of deck repair if salting continues; the quantity of CMA required to achieve acceptable deicing; and attendant CMA storage, handling, and spreading costs. Changes in any of these assumptions, as well as the discount rate employed, have significant effects on cost comparisons. Among the numerous considerations not addressed in the example are effects on nondeck bridge damage, effects on motorists using the bridge, and the cost-effectiveness of other deicers and mitigation measures.

The example indicates that simple generalizations cannot be made about the types of situations in which selective application of CMA might be appropriate.

OUTLOOK FOR REDUCING DEICING COSTS

More than 20 years after the adverse side effects of road salt first came to light, the total cost of salting continues to be high. Major achievements in corrosion protection have helped control some of these costs and are expected to continue to do so in the future. In addition, carefully designed and well-located salt storage facilities and better-managed salting programs should help reduce environmental damage and water contamination.

The efficient use of salt should continue to be an important priority in winter maintenance programs. Demands on highway agencies for fast and effective deicing, however, sometimes result in indiscriminate salting. However, new developments in winter maintenance—including deicer application techniques (e.g., salt prewetting), plowing and spreading equipment, and weather and roadway monitoring (e.g., pavement sensors)—are making these priorities less conflicting. Sodium chloride is likely to continue to be the predominant highway deicer for many years to come. Nevertheless, highway agencies and private industry continue to refine and seek new means of preventing and treating salt's adverse effects, for example, by improving corrosion protection and developing new corrosion repair and treatment methods. Likewise, research continues aimed at reducing salt use by developing anti-icing technology (e.g., chemicals for pre-treating roadways to prevent ice formation), improving salt application techniques, and exploring deicer alternatives to salt.

CMA is one of many options available to highway agencies for reducing salt's adverse effects. As experience with CMA increases, knowledge about its use characteristics will increase. The decision to use CMA can be made only on a case-by-case basis, taking into

TABLE 7-1 HYPOTHETICAL USE OF SALT AND CMA FOR HIGHWAY STRUCTURES AND COMPARATIVE COSTS

Approximate Bridge or Viaduct Dimensions ^a	Continued Salting: Present Value Cost ^b (\$ millions)				Conversion to CMA: Present Value Cost ^c (\$ millions)	
	Early/ High-Cost Repair ^d	Early/ Lower-Cost Repair ^e	Late/ High-Cost Repair ^f	Late/ Lower-Cost Repair ^g	High Quantities of CMA ^h	Low Quantities of CMA ⁱ
1 mi (500,000-ft ² deck)						
5% discount rate	12.9	6.6	7.8	4.0	5.6	4.0
10% discount rate	7.9	4.0	2.8	1.5	2.9	2.0
½ mi (250,000-ft ² deck)						
5% discount rate	6.5	3.4	4.0	2.1	4.7	3.3
10% discount rate	4.0	2.0	1.5	0.8	2.4	1.7
¼ mi (125,000-ft ² deck)						
5% discount rate	3.3	1.8	2.1	1.1	4.2	3.0
10% discount rate	2.0	1.1	0.8	0.4	2.2	1.5

NOTE: Hypothetical structures are on Interstate highway with six 12-ft lanes and two 9-ft shoulders (90-ft-wide deck).

^aAssumes that structures are poorly protected against corrosion and are not yet critically contaminated with salt. Also assumes that calcium chloride is not normally used.

^bAll costs are calculated for 50 years and discounted to present value using annual discount rates of 5% and 10%. Assumes a direct cost of salting of \$55 per ton, including material, spreading, handling, and storage costs. Assumes that the bridge deck and 1 mi of approach highway in each direction are salted at an annual application rate of 15 tons per lane-mi.

^cAll costs are calculated for 50 years and discounted using discount rates of 5% and 10%. Assumes direct CMA costs of \$700 per ton, including material, spreading, handling, and storage costs. Includes the cost of applying CMA to the bridge deck plus 1 mi of approach highway in each direction. Assumes that no significant amounts of salt will be carried to the deck from beyond the 1-mi approaches. Assumes no chloride deicers (including calcium chloride) are used on the deck. Assumes no rehabilitations or other major repairs will be required during the 50-year period.

^dAssumes that major deck rehabilitation will be required after 10 years. Rehabilitation involves total replacement of concrete and installation of an effective salt protection system at a cost of \$40/ft².

^eAssumes that major deck rehabilitation will be required after 10 years costing \$20/ft².

^fAssumes that major deck rehabilitation will be required after 20 years costing \$40/ft².

^gAssumes that major deck rehabilitation will be required after 20 years costing \$20/ft².

^hAssumes that 1.7 times more CMA (by weight) will be applied than salt (i.e., 25.5 tons per lane-mi).

ⁱAssumes that 1.2 times more CMA (by weight) will be applied than salt (i.e., 18 tons per lane-mi).

consideration other deicers and mitigation measures available. CMA's use and acceptance is likely to depend in large part on the progress made in these other areas.

NOTE

1. CMA does not ionize as readily as NaCl, thereby slowing initial action. In addition, because acetate ions are larger than chloride ions, the rate of diffusion into the liquid film surrounding ice is slower, which further delays reaction time compared with NaCl.

APPENDIX A

State Highway Agency Questionnaire

Name of Respondent _____ State _____
Title _____ Phone _____

SURVEY OF DEICING CHEMICAL USAGE AND MITIGATION MEASURES

1. Does your agency use chloride deicing salts (sodium chloride or calcium chloride)?

☐ No. If no, please answer question 9 and return survey.

☐ Yes. If yes, please specify:

Total annual tonnage _____ tons

Pct sodium chloride _____ %

Pct calcium chloride _____ %

2. What is the extent of salt usage in your state?

☐ Widespread

☐ Limited to parts of the state. If limited, please specify:

Locations where used (generally). _____

Percent of state mileage treated _____ %

3. Please specify the approximate minimum, maximum, and average salt usage on state-maintained highways in terms of annual tons per lane-mile (by highway type if possible).

Highway Type	Annual Tons/Lane-Mi			# of Treated Miles
	Min	Max	Avg	
Urban interstate				
Urban primary				
Other urban				
Rural interstate				
Rural primary				
Rural secondary				
Other rural	_____	_____	_____	_____
Total	_____	_____	_____	_____

4. Are salt application decisions and rates based on a prescribed agency policy?

[] No

[] Yes. If yes, briefly explain the policy. _____

5. Does your agency use other deicing chemicals in addition to common sodium chloride or calcium chloride (e.g., CMA, corrosion-inhibiting salt additives)?

☐ No

☐ Yes. If yes, please identify the type of alternative, the amount used per year (in tons), and the circumstances when used. _____

6. Does your agency have a policy for reducing salt usage on highways in environmentally sensitive areas (such as forests or parklands) or near water supplies?

☐ No

☐ Yes. If yes, how many miles are affected? _____ miles

7. In recent years, has your agency received any complaints or been involved in litigation related to road salt impacts on water supplies or the natural environment?

☐ No

☐ Yes. If yes, please specify which areas have attracted the most complaints (e.g., water supplies, damage to roadside vegetation, etc.).

Is the annual number of complaints increasing?

☐ Yes ☐ No

How many complaints did you receive last year? _____

8. Is your agency (or another state agency) taking measures to monitor or mitigate (e.g., special drainage systems, relocation of private wells) the effect of highway salt runoff on the natural environment or drinking water?

☐ No

☐ Yes. If yes, please explain. _____

If the annual dollar cost of these measures is known, please specify. \$ _____

9. Which bridge deck protective systems are used most frequently by your agency on new bridges or completely replaced bridge decks?

10. What has been the trend in salt use in your state in recent years?

☐ Upward ☐ No change ☐ Downward

If upward, by how much since 1980? _____ %

If downward, by how much since 1980? _____ %

11. What is your agency's total annual budget for snow and ice removal?

Total \$ _____ (include expenditures on contract work)

If possible, please specify expense by:

Equipment _____ %

Manpower _____ %

Deicing Chemicals _____ %

Abrasives _____ %

Other _____ % (please specify _____)

12. Do local highway agencies (county, municipal, toll) in your state use road salt?

☒ No

☐ Yes. If yes, estimate the total amount they use as a percentage of state salt use. _____ %

13. Does your state regulate local agency salt use or offer any guidance on salt use practices?

☐ No

☐ Yes. If yes, please explain. _____
